APPLICATION OF CROP SIMULATION MODELS FOR WATER AND NUTRIENT MANAGEMENT ON GROWTH AND PRODUCTIVITY OF RICE UNDER DIFFERENT CLIMATE SCENARIOS

Thesis submitted to
the University of Calicut in partial fulfilment of
the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY
in
BOTANY

by
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This is to certify that the thesis entitled "**Application of crop simulation model for water and nutrient management on growth and productivity of rice under different climate scenarios**" submitted to the University of Calicut by **SRUTHI P** in partial fulfilment for the award of the degree of Doctor of Philosophy in Botany is a bonafide record of research work done under my guidance and supervision in the Land and Water Management Research Group, Centre for Water Resources Development and Management, Kozhikode. No part of this work has been presented elsewhere for any Degree or Diploma previously.

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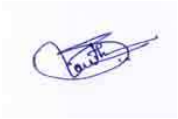
DECLARATION

I hereby declare that the work presented in the thesis entitled **"Application of crop simulation models for water and nutrient management on growth and productivity of rice under different climate scenarios"** is based on the original work done by me under the guidance of Dr. U. Surendran and has not been included in any other thesis submitted previously for the award of any degree. The contents of the thesis are undergone plagiarism check using iThenticate software at C.H.M.K. Library, University of Calicut, and the similarity index found within the permissible limit. I also declare that the thesis is free from AI generated contents.

Signature 

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This thesis is gratefully dedicated
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Abstract

Rice, the second most vital cereal crop globally, plays a crucial role in culture, lifestyles, and ecosystem services. Despite its significance, challenges such as industrialization, resource constraints, and climate change threaten global food security. This study focuses on rice production in Kerala, where a sharp decline in area and production was observed for the past 20 years and given the ongoing climate changes, this scenario is anticipated to worsen in the future. The objective of this research was to identify optimal management practices for rice, focusing on water and nutrient requirements to enhance its growth and maximize production. This goal was accomplished through a comprehensive approach involving field experiments, crop modelling, and simulation studies. Furthermore, the investigation sought to evaluate the influence of diverse environmental factors on rice growth and production, particularly under varying climate scenarios. The research aims to address this issue by assessing the Crop Simulation Model (CSM) for rice under diverse climatic scenarios and proposing sustainable management practices, which will improve the crop and water productivity. The study outlines seven experiments conducted from 2018 to 2023, focusing on nutrient and water management strategies, post-harvest field management, and greenhouse gas emissions mitigation. Results from experiments reveal the impact of different irrigation and nutrient management strategies on rice varieties, emphasizing the importance of optimizing practices for enhanced crop performance and resource conservation. The experiment showed a significant 37.52% water savings through alternate wetting and drying compared to conventional flood irrigation. Additionally, the study explores aerobic rice management techniques as water-saving technologies, providing valuable insights into nutrient and planting strategies in which Direct Seeding of Rice (DSR) with 125 % inorganic fertilizers exhibited superior yield and growth characteristics. The research also delves into effective water nutrient management practices for aerobic rice in midland lateritic soils, emphasizing the significance of incorporating cocopeat to combat water stress. Furthermore, experiments evaluating organic management practices showcase the potential benefits of combining compost and Azolla for improved crop yield and soil health. Post-harvest field management strategies are explored to mitigate greenhouse gas emissions, with Non-Winter Flooding and Late Straw Incorporation proving effective. Furthermore, DSSAT-CERES Rice model was calibrated and validated for aerobically grown *Uma* rice cultivar with field experiment data. The study employs the Crop

Simulation Model and spatial techniques, simulate crop yield under various management practices, projecting a decline in rice production with increasing temperatures. Also assessed the impact of climate change on paddy farming in Kozhikode and Palakkad districts using the temperature data from CMIP6 SSP 2-4.5 and SSP 5 -8.5 in different models (CMCC-ESM2, EC-Earth3, EC-Earth3-Veg, and GFDL-CM4) for the future yield prediction. The study indicates that climate change is likely to negatively impact paddy yield with a corresponding increase in temperature. Further the study highlighted the potential adaptation measures, such as altering sowing dates and fertilizer management. In conclusion, this research offers valuable insights into site-specific nutrient and water management strategies affecting rice yield and provides recommendations for sustainable agricultural practices. The findings emphasize the need for precision farming, water-efficient technologies, and adaptation measures to ensure food security and support Kerala's goal of becoming carbon-neutral by 2050.

സംഗ്രഹം

ആഗോളതലത്തിൽ പ്രധാനപ്പെട്ട ധാന്യവിളയായ നെല്ലിന്റെ വളർച്ചയിൽ മണ്ണും കാലാവസ്ഥയും ഗണ്യമായ പങ്കാണ് വഹിക്കുന്നത്. കേരളത്തിൽ നെൽകൃഷിയും അരി ഉൽപാദനവും കുത്തനെ കുറയുന്ന സാഹചര്യത്തിൽ, നിലവിലുള്ള കാലാവസ്ഥാ വ്യതിയാനങ്ങൾകൂടി കണക്കിലെടുത്താണ് ഈ പഠനം നടത്തിയിട്ടുള്ളത്. നെല്ലുൽപാദനം വർധിപ്പിക്കുന്നതിന് ആവശ്യമായ സമീകൃത ജല- പോഷക പരിപാലന രീതികൾ തിരിച്ചറിയുക എന്നതായിരുന്നു ഈ ഗവേഷണത്തിന്റെ ലക്ഷ്യം. ഫീൽഡ് പരീക്ഷണങ്ങൾ, ക്രോപ്പ് മോഡലിംഗ്, സിമുലേഷൻ പഠനങ്ങൾ എന്നിവയിലൂടെയാണ് ഈ ലക്ഷ്യം കൈവരിച്ചത്. ഇതിനായി, 2018 മുതൽ 2023 വരെ ഏഴ് വ്യത്യസ്ത പരീക്ഷണങ്ങൾ നടത്തി. വ്യത്യസ്ത ജല- പോഷക പരിപാലന രീതികൾ, ഹരിതഗൃഹ വാതക ബഹിർഗമനം ലഘൂകരിക്കൽ, വിവിധ നടീൽ രീതികൾ എന്നിവയിൽ പഠനങ്ങൾ നടത്തി. ഇവയിൽ കുറഞ്ഞ വിഭവങ്ങൾക്കൊണ്ട് പരമാവധി വിളവ് ലഭിക്കുന്ന രീതികൾ കണ്ടെത്തി. പരമ്പരാഗത വെള്ളം-കെട്ടിനിർത്തിയുള്ള (Flooding) ജലസേചനവുമായി താരതമ്യപ്പെടുത്തുമ്പോൾ, കയറ്റിറക്ക് ജലസേചനരീതിയിലൂടെ (Alternating wetting and drying) 37.52 % ജലം ലാഭിക്കാനാകുമെന്ന് ഈ പഠനം കണ്ടെത്തി. കരനെല്ല് (Aerobic rice) കൃഷിയിൽ 125 % രാസവളപ്രയോഗവും നേരിട്ടുള്ള വിത്ത് വിതയ്ക്കൽ (Direct seeding rice) രീതി മികച്ച വിളവും വളർച്ചയും നൽകുന്നതായി കണ്ടു. കൂടാതെ ഈർപ്പം ആഗിരണം ചെയ്യുന്ന പദാർത്ഥങ്ങൾ (ചകിരി ചോറ്) ചേർക്കുന്നതിലൂടെ മണ്ണിന്റെ ജലാംശം നിലനിർത്തുകയും ഇത് ചെടിയിൽ അനുഭവപ്പെടുന്ന വരൾച്ച കുറയ്ക്കാൻ സഹായകരവുമാവും. കമ്പോസ്റ്റും അസോളയും ചേർന്നുള്ള ജൈവവളപ്രയോഗം മെച്ചപ്പെട്ട നെല്ലുൽപാദനത്തിനും മണ്ണിന്റെ ഫലഭൂയിഷ്ഠത വർദ്ധിപ്പിക്കാനും സഹായിക്കുന്നു. കൂടാതെ ഈ പരീക്ഷണ ഡാറ്റ ഉപയോഗിച്ച് ഉമ നെല്ലിനത്തിന് വേണ്ടി DSSAT-CERES Rice മോഡൽ വാലിഡേറ്റ് ചെയ്യുകയും ചെയ്തു. വിവിധ CMIP6 - SSP 2-4.5, SSP 5-8.5- മോഡലുകളെ (CMCC-ESM2, EC-Earth3, EC-Earth3-Veg, GFDL-CM4) ഉപയോഗിച്ച് കോഴിക്കോട്, പാലക്കാട് ജില്ലകളിലെ നെൽകൃഷിയിൽ കാലാവസ്ഥാ വ്യതിയാനം ചെലുത്തുന്ന ആഘാതം വിലയിരുത്തുകയും ഭാവിയിലെ നെല്ല് ഉൽപാദനത്തിലെ തോത് പ്രവചിക്കുകയും ചെയ്തു. കാലാവസ്ഥാ വ്യതിയാനവും താപനിലയിലെ വർധനവും നെല്ല് ഉൽപാദനത്തെ പ്രതികൂലമായി ബാധിക്കുമെന്ന് പഠനം കണ്ടെത്തി. ഈ ഗവേഷണം, നെൽകൃഷിയിലെ കൃഷിയിട പോഷക, ജലസംരക്ഷണ, ജലസേചന, സുസ്ഥിര കാർഷിക രീതികൾ എന്നിവയിൽ വിലപ്പെട്ട ശുപാർശകൾ മുന്നോട്ട് വയ്ക്കുകയും ചെയ്യുന്നു. ഭക്ഷ്യസുരക്ഷ ഉറപ്പാക്കുന്നതിനും 2050-ഓടെ കാർബൺ ന്യൂട്രൽ ആകുകയെന്ന കേരളത്തിന്റെ ലക്ഷ്യത്തെ പിന്തുണയ്ക്കുന്നതിനും സഹായകരമാകുന്ന നൂതനവും കാര്യക്ഷമവുമായ, കൃഷിരീതികൾ, സാങ്കേതികവിദ്യകൾ എന്നിവയുടെ ആവശ്യകത കൂടി ഈ പഠനം ശുപാർശ ചെയ്യുന്നു.

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ABBREVATIONS

AWD	:	Alternating Wetting and Drying
BMP	:	Best Management Practices
C	:	Carbon
CERES	:	Crop Environment Resource Synthesis
CSM	:	Crop Simulation Models
DAT	:	Days After Transplanting
DSR	:	Direct Seeded Rice
DSS	:	Decision Support System
DSSAT	:	Decision Support System for Agro-Technology Transfer
ET	:	Evapotranspiration
FYM	:	Farm Yard Manure
GDP	:	Gross Domestic Production
GHG	:	Greenhouse Gases
Gt CO_2-eq	:	Gigaton of Carbon dioxide Equivalent
ha	:	Hectare
hr	:	Hours
HYVs	:	High Yielding Varieties
K	:	Potassium
kg	:	Kilogram
kg ha^{-1}	:	Kilogram /Hectare
lakh ha	:	Lakh Hectare
ML	:	Membrane Leakage
mm	:	Millimeter
MMT	:	Million Metric Tons

Mm/ dec	:	Millimeters per Decade
N	:	Nitrogen
^{o}C	:	Degrees Celsius
P	:	Phosphorus
PMD		Physiological Maturity Day
ppm	:	Parts Per Million
PWP	:	Permanent Wilting Point
RWC	:	Relative Water Content
SOC	:	Soil Organic Carbon
T	:	Ton
WP	:	Water Productivity

Introduction

1. Introduction

The second most important cereal crop in the world is rice, after maize crop and it also contributes to the enrichment of culture, lifestyles and ecosystem services. Rice requires highly specific environmental conditions to grow and is successfully grown in several parts of the world for numerous purposes. Asian countries are the major contributors of rice in the globe. With 165.25 million ha of agricultural land worldwide, 502.98 MMT of rice were produced globally in 2022–2023. However, in 2021–2022, China produced 148.99 MMT of milled rice, more than any other country. India came in second with 129.47 MMT, followed by Bangladesh with 35.85 MMT. Around 510.3 million metric tons of milled rice were used worldwide in 2021–2022. Which, China was by far the world's largest consumer of rice in 2021/ 22, consuming almost 155 MMT of milled rice annually. India is ranked second after China, consumed 103.5 MMT of rice during the same time period (apps.fas.usda.gov). Population expansion in countries like Africa and Asia is driving future rice demand, with global demand expected to be around 584 MT or less by 2050 (Samal et al., 2022; Rezvi et al., 2023). Rice is a vital nutrition crop for more than a fifth of the global population, this prediction might emphasise the significance of ensuring food security. However, challenges like industrialization, crop diversification, resource constraints, and climate change make plans crucial for food security.

India's agriculture is the main contributor to its GDP, with agriculture and related industries growing at a rate of 10 % annually. As the world's largest rice-growing country, India accounts for over 40 % of food grain output and employs 70 % of rural residents (Kumar et al., 2019). The most important rice-producing states are West Bengal, Odisha, Uttar Pradesh, Andhra Pradesh, Punjab, Bihar, Tamil Nadu, and Chhattisgarh. However, rice yields differ significantly across India. Even in districts with high rice-growing land, yields are low, which drags down the national average (DoES, 2023). This is the root cause of the country's low productivity especially compared with countries like China (Surendran et al., 2021).

1.1. Challenges faced by Kerala rice production

Kerala has a humid tropical climate with heavy rainfall, high humidity, and abundant sunshine. It is divided into three topography zones: Western Ghat highland, coastal lowland, and midland zone. The state's diverse agro-ecological conditions make it

easy to cultivate a variety of crops, from semi-arid to temperate. However, the majority of crops' production is trending lower, making the state's agriculture productivity problem complicated and influenced by a variety of variables.

Rice cultivation stands as a cornerstone of agricultural practices in the Indian state of Kerala, playing a pivotal role in ensuring food security and livelihoods for a significant portion of the population. Kerala ranked as the 18th largest producer of paddy in India. The production and area of rice have been declining consistently over the last several years. In Kerala, 8.76 lakh ha of paddy cultivated land in 1980-81 was reduced to 1.95 lakh ha in 2021-22. During 1980-81, 1.29 MT was the rice production whereas today, 2021-2022, it is 562097 ton (DoES, 2023). Kerala state with a low base in food production is facing serious challenges in retaining even this meagre area. Since the mid-1970s, Kerala's agricultural economy has been undergoing structural change. A significant amount of the region's traditional crop-land, which was used for subsistence crops like tapioca and rice, has been converted to more lucrative plantations and crops like bananas. (spb.kerala.gov.in).

Kerala's economy is primarily agricultural due to abundant water resources, rainfall, and terrain. However, irregular rainfall distribution results in a long dry spell and moisture stress, hindering productivity (Varadan, 1996; Surendran et al., 2015, 2019; Chaturvedi et al., 2019). The soil type is predominantly laterite, with large-particle and low-water-holding gravel soils due to loss of organic matter and fine-textured topsoil. This, along with the soil's poor water-holding capacity, makes soil moisture stress- a key barrier to increased productivity in the State. The State's low irrigation efficiency is largely due to the lack of location-specific scientific data on crop irrigation scheduling, which should be based on soil types and agro-ecological environments (Raine et al., 2007; Surendran et al., 2015; Yohannes et al., 2019).

Climate change is acknowledged as one of the most important concerns confronting humanity today. Anthropogenic activities have caused an increase in atmospheric CO_2 concentration from 280 ppm in pre-industrial times to approximately 400 ppm and is increasing at a rate of roughly 2 ppm/ year, with the mean global temperature rising by 0.8 ^{o}C since 1880 and potentially 5-7 ^{o}C by 2100 (IPCC, 2007a, b; WMO 2008; Hashimoto, 2019; Hamza et al., 2020; Dong et al., 2024). Kerala also experienced a significant increase in temperature between 1956 and 2004, with a maximum temperature of 0.64 °C and a

minimum of 0.23 °C (Surendran et al., 2014). The annual average temperature increased by 0.44 °C. This tendency was also observed at the Centre for Water Resources Development and Management in Kozhikode between 1983 and 2010 (Joseph et al. 2011; Jayakumar et al., 2016; Surendran et al., 2017).

Greenhouse gas (GHG) emissions have as well, increased since 2000 (Le Quéré et al., 2013), despite efforts to curb them. To mitigate this, large-scale deployment of negative emissions technologies is being considered, with soil carbon sequestration having a global mitigation potential of 4.8 Gt CO_2-eq in 2030 (Smith et al., 2013; Riahi et al. 2015; Singh, et al., 2023). Methane, a significant greenhouse gas, contributes to global warming by 20 % since pre-industrial times. Rice cultivation, mainly due to water and straw management, is a major source of agricultural CH_4 emissions (Kirschke et al., 2013; Saunois et al., 2016; Martínez-Eixarch et al., 2018, 2021; Dutta et al., 2022). Apart from growing season rice management, post-harvest rice field management is also crucial in GHG emission control. However, the works on similar lines are very few and need more research for a clear understanding of the GHG emission from paddy fields. So, the combination of changing climate patterns and increasing agricultural demand presents challenges for sustaining rice productivity.

1.2. Crop Simulation Models

Climate change has been predicted to impact the productivity of some crops, such as rice, wheat, maize, sorghum, and mustard, while others, like potato, soybean, and coconut, are projected to gain (Pathak et al., 2003; Kumar & Aggarwal, 2013; Kumar et al., 2013; Surendran et al., 2014; Jayakumar et al., 2017; Kingra et al., 2019; Marcinkowski & Piniewski, 2024). Adaptation is necessary to maximize the benefits of climate change in specific areas while minimizing its negative effects (Saeed et al., 2023). Crop simulation models (CSMs) are crucial for managing agricultural resources. A model is a computer-based program that simulates crop growth and development based on soil, weather, and crop management variables. It helps in understanding and improving the system's performance (Abimbola et al., 2022).

CSMs have been used for over 40 years to study crop systems, but few studies in upland Kerala use them to manage crops. Field research in Kerala mostly empirical and site-specific, with no active aid from agricultural system models. Integrating system models with field research will make it easier to interpret results and eliminate knowledge

gaps. As climate change accelerates, the impact on agriculture is becoming more pronounced, with altered precipitation patterns, temperature extremes, and unpredictable events. CSMs provide a predictive framework to assess water availability, nutrient dynamics, and rice growth under diverse scenarios, helping identify the most promising input combinations and sustain production systems.

1.3. Research problem

The area and production of any crop are determined by a variety of factors such as land fertility, irrigation, fertilizer application, climate charges, marketing facilities and the availability of agricultural labourers. The reduction in productivity of crops and its effects are very crucial and need to pay attention to how climate changes in Kerala affect plant growth and development and the impact of different post-harvest rice field management and GHG emissions from these paddy fields towards these changing environments.

The majority of studies attempting to measure the advantages of drought and nutrient stress on agriculture and the environment have concentrated on arid and semi-arid regions, where irrigation is crucial to output and water supply is becoming more scarce and costly. The reasoning behind drought and nutrient needs, however, must be carefully considered in humid tropical environments where rainfall plays a significant role in crop evapotranspiration requirements. This is especially true when considering the potential savings on water and energy that could result from using a different scheduling strategy. Hence such a study is required to optimize the water and nutrient inputs for obtaining maximum productivity and less damage to the environment in changing climatic scenarios. The validated crop simulation models (CMS) will help in identifying the best management strategies to maximize production sustainably and GIS and remote sensing coupled with modelling tools are indispensable for assessing, monitoring, and managing rice cultivation in the context of climate change. With this background, the present work has been chosen for the PhD research program to assess the CSM for rice under different climatic scenarios and suggest better management practices to achieve sustainable rice production.

1.4. Objectives

The objectives of the current study are to contribute to an understanding of the effects of different climate scenarios on the rice and how they deal or adapt with it.

- Establish nutrient and water recommendations for rice using field experiments and crop simulation model.
- To quantify the impact of weather, soil and water on the changes in rice growth and yield parameters using sensitivity analysis of the simulation model.
- To predict the rice productivity for future climate scenarios and suggest Best Management Practices (BMPs) for improving the productivity under different climatic scenarios.

Review of Literature

2. Review of Literature

2.1. Rice cultivation and its status

Rice (*Oryza sativa* L.) is important grain crop that is grown all over the world, feeding more than half of the population. The majority of Keralites eat rice as their basic cuisine. Due to the population explosion, by 2035 and 2050 global demand for rice production will increases by 26 % and 50 % respectively. The global food demands and extreme climate events are likely to reduce crop yield including rice production which in turn threatens food security (Alauddin et al., 2020, Surendran et al., 2021). This will negatively impact the livelihood of Asians, especially in Kerala, India since rice is their principal food crop. Aside from this, there are numerous constraints involved with rice cultivation, namely a huge water demand (1000–2000 mm) for puddling and maintaining continuous flooding (Surendran et al., 2021), soil quality loss, yield loss, higher labor inputs, and overdosage of agrochemicals have made it expensive for several farmers, particularly small farmers. India's population will exceed 1400 million by the year 2025. Then they will require 300 million ton of food grain, compared with about 200 million ton today. So, food security has been a major worry for India. Water shortage, climatic changes, environmental calamities, and low soil fertility will all contribute to a far worse condition in the result, increasing crop productivity has become India's primary goal, and farmers are using surplus water and chemicals to achieve so (Jayakumar et al., 2023) To attaining maximum crop growth and grain yield farmers frequently apply excess nitrogen (N) fertilizers (E.g.: Urea) and water than the optimum requirement. The extra water does not benefit the plant since it percolates or runs off the field. However, excessive use of fertilizers reduces soil fertility and disturbs soil texture in the long run. The technique of application, as well as the appropriate management of agrochemicals, is very vital to acquire the intended results without causing an environmental population (Jayakumar et al., 2023). Furthermore, persistent production of rice, frequently under poor soil and crop management techniques, results in loss of soil fertility, indicating multi-nutrient deficits (Dwivedi et al., 2012).

2.1.1. Importance of rice cultivation

One of the essential elements of a healthy diet is cereal. Moreover, 40 % of the world's population considers rice to be a dependable food source, making it one of the

most popular cereals in the world. More than any other cereal, rice provides a good source of carbs, iron, calcium, thiamine, and vitamin E. Nearly 35 % of the energy and 28 % of the protein in rice. Additionally, those who consume rice in their diet receive nutrients and dietary fibre from it. The top two rice-producing nations are China and India, and Asian nations account for 90% of the world's rice production. In India, rice is grown on 44.5 million ha of land, yielding 172.6 million tons of rice. Rice cultivation employs nearly 70 % of the rural population. At present India is cultivating more than 4000 cultivars of rice.

2.1.2. Rice Cultivation in India

In India rice has been grown under different agro-climatic region which varies in altitude and climate. It has been found adapted to the high mountainous regions and also to the below sea level regions. The average temperature required for rice cultivation is 21 to 37 ºC and is suitable in the region with an annual rainfall of 150-300 cm. As a result, rice growing seasons vary across India, depending on temperature, soil, precipitation, water availability, and other factors. While in southern and eastern regions of the country, climatic conditions were found favourable hence rice cultivation can be carried out throughout the year. Autumn, winter, and summer are the three main growing seasons for rice in India, and these seasons are categorized according to when the crop is harvested. The precise window of sowing varies between Indian states and is largely influenced by weather (monsoon-rainfall) or the water from irrigation projects. Yield is also influenced by the period of sowing, the variety used, and other factors. Similar names for the seasons are given locally in accordance with local customs and culture. For example, the autumn rice crop is referred to as "Bhadai" in Bihar, "Virippu" in Kerala, "Aus" in West Bengal, "Beali" in Orissa, "Kuruvai/ kar/ Sornavari" in Tamil Nadu, and "Ahu" in Assam (Surendran et al., 2021). *Kharif* is the main growing season in the country. Rice is grown under rainfed conditions and irrigated conditions. Irrigated rice covers roughly 22 million ha of the country's total rice production area. Rainfed conditions consist of both upland and lowland rice production (Singh, 2009).

The top three rice-producing states in India as of 2020–21 is mentioned below: West Bengal, Uttar Pradesh, Andhra Pradesh and Punjab. These three states provide about 36 % of India's total rice production. Thirteen percent of India's total rice production came from West Bengal. Of the rice produced in India, Uttar Pradesh produced 12.81 % of it (FAOSTAT, 2022; www.statista.com).

2.1.3. Rice Cultivation in Kerala

One of the attractive features of Kerala state is its luxurious green paddy field, even though the area under rice cultivation is reducing since the 1980s. However now rice occupies the third position when compared with other crops regarding area under cultivation, first two positions are handled by coconut and rubber (Thomas, 2011). Major rice-producing districts of Kerala are Palakkad and Alappuzha, the former is considered as the "Rice bowl of Kerala". In Alappuzha, Kuttanad which is gifted with a large system of backwaters supports rice production.

In many regions of Kerala, rice cultivation has been carried out in such a manner that enriches certain geographical and ecological features of those regions *e.g. kaipad* fields, *pokkali* fields, *kole* fields etc. In Kerala rice productivity is less *i.e.* nearly 2790 kg ha^{-1} but higher than the Indian average (2424 kg ha^{-1}). In Kerala, the paddy area decreased from 8.7 lakh ha in 1975–1976 to 2.05 lakh ha in 2020–21. Paddy production fell from 13.31 lakh ton to 6.3 lakh ton during that time. When the state produced 4.3 lakh ton of paddy in 2016–17, production reached its lowest point. From 1587 kg ha^{-1} in 1980–81 to 3091 kg ha^{-1} in 2020–21, paddy production grew (DoES, 2023). However, the sharp drop in the area covered by paddy and the subsequent production decline cancels out the increase in productivity. Along with several environmental and ecological issues, the decrease in rice-growing land and the ensuing decrease in paddy yield have contributed to Kerala's problem of food insecurity. A large range of goods and services are directly and indirectly provided by the environment of the rice-growing agricultural wetland. Paddy field conversion has a lot of negative social, economic, and environmental effects.

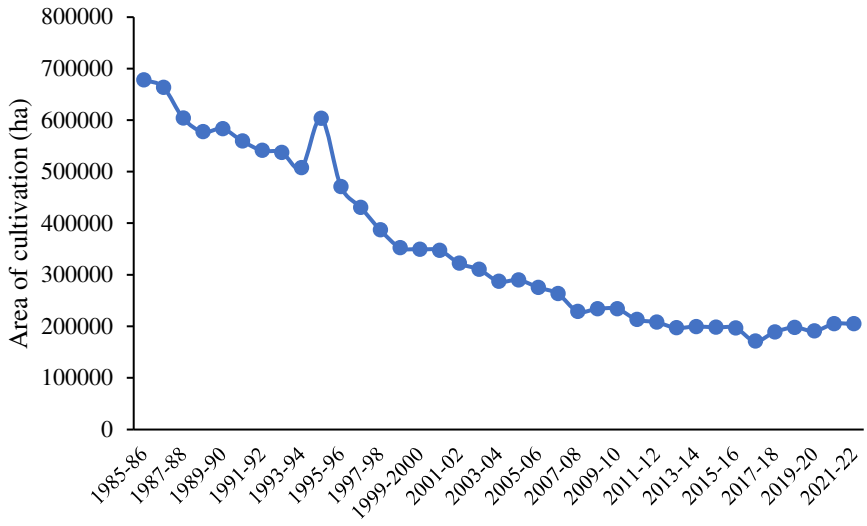


Fig.2.1. Paddy area of cultivation in Kerala during 1985 to 2022

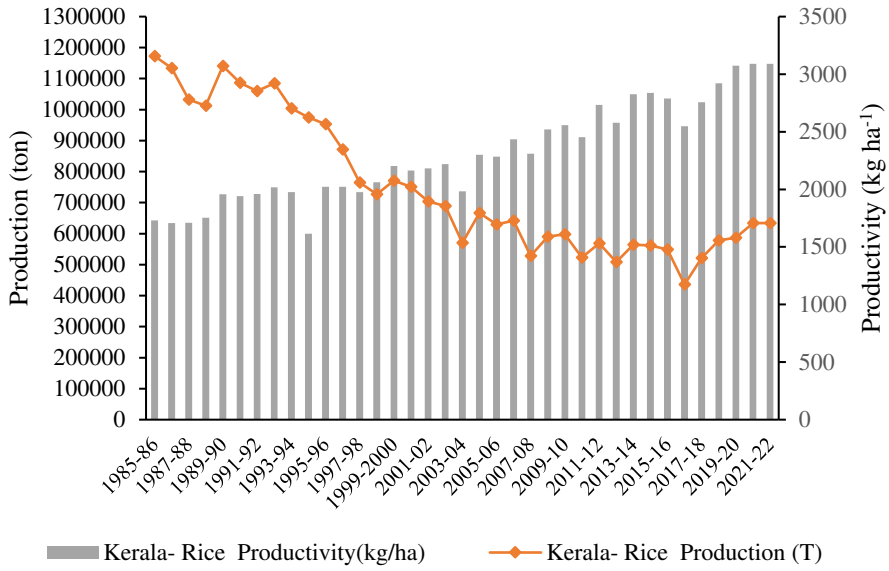


Fig.2.2. Paddy production and productivity of Kerala during 1985 to 2022

The diagrammatic representation of area, production, and productivity of paddy during 1985 to 2022 is given (Fig.2.1 & Fig.2.2). The area under cultivation reached the highest level in 1985-86, i.e. 6.78 lakh ha. The lowest figure was noted in the year 2016-17, i.e. 1.71 lakh ha. Highest production was achieved in 1985-86, i.e. 11.73 lakh ton and the lowest level in 2016-17, i.e.4.36 lakh ton. Productivity is achieved the highest during 2021-22 (3091 kg ha^{-1}) and lowest values in 2006-07 (1800 kg ha^{-1}).

Kerala's paddy production has steadily decreased since the 1980s. Kerala's economic, ecological, and social development has been significantly impacted by the steep decline in the state's paddy-growing area and rice production. However, there have been encouraging signs of a rebound in Kerala's rice production over the past five years. Kerala's Department of Agriculture Development and Farmers' Welfare is implementing a rice development program with an outlay of ₹ 9510 lakh for 2023-24. The program includes input assistance for sustainable rice development, support for group farming activities, and royalty to paddy landowners. It also includes soil and root health management and productivity improvement, area expansion, Registered Seed Growers Programme, Seed Village Programme, Operation Double Kole, and group farming activities. The department also has other schemes to promote agriculture in Kerala, such as farm plan-based production, vegetable development, coconut development, spices, supply chain development, state crop insurance schemes, and more (keralaagriculture.gov.in;

keralaagriculture.gov.in; spb.kerala.gov.in; www.indiatoday.in). Paddy farmers all around the state are now showing a renewed sense of purpose and zeal.

2.2. Water management strategies in rice cultivation

Agriculture depends on a climate and any change in that alters crop productivity. Climate change situations include higher temperatures, precipitation changes, and higher atmospheric CO_2 concentrations (Nazir et al., 2020). Elevated $C0_2$ accelerated rice development, increased leaf photosynthesis activity by 30-70 per cent and crop yield by 15-30 per cent, depending on its environment and genetic makeup and its environment. Under optimum temperature conditions, a significant increment in grain yield can be observed in those CO_2-responsive rice varieties. However, higher temperatures would lower the yield and quality of rice. Spikelet sterility is caused by heat waves beyond certain temperature/ humidity thresholds. Grain yield decreased by 10 % for every 1 °C increase in growing-season lowest temperature in the dry season, but the effect of maximum temperature on crop yield was minimal. Hence, increasing temperatures shorten the growth season, which results to decreasing yields, whereas elevated CO_2 promotes enhanced yields (Erda et al., 2005). As a result, we must research water-saving methods to combat the effects of climate change and engage in more sustainable rice growing.

2.2.1. Water Requirement of Rice

The seasonal water consumption of rice fields includes water used for land preparation as well as water required to compensate for crop growth losses due to seepage, evaporation, transpiration, and percolation. The majority of the water sprayed during crop development is not used immediately for transpiration and so considered lost from fields (Dhinesh et al., 2019). Typically, water input for rice varies between 660 to 5280 mm depending on the environmental factors, growth season, growing period length of the growing period, climatic conditions, soil type, and hydrological parameters (Tripathi, 1996; Gupta et al., 2002; Tuong & Bouman, 2003; Surendran et al., 2021). According to soil type and its texture, seasonal water input to rice in India was found to be ranging from 1566 mm to 2262 mm, in clay loam soil and sandy loam soil respectively, with variations due to significant percolation losses. In Kerala, the total annual water demand for rice ranged between 852 to 2362 mm. In rice production, the ET normally varies from 35 to 50 % of the total water requirement, depending on the type and length of the growing season. For instance, in the Thrissur District, the Triveni rice variety

experienced 7.42 mm per day of evapotranspiration and 17.15 mm per day of percolation, resulting in a total seasonal water loss (Chirayath et al., 1998).

The increased water input in rice is mainly due to water requirements for land preparation and puddling, and the seepage and deep percolation losses (to groundwater) associated with continuous flooding. Depending on the soil type and water table, seepage and percolation losses might range between 25 % and 85 % of total water input (Cabangon et al., 2001; Dong et al., 2004). At the field level, a farmer's losses from seepage and percolation are frequently genuine, but at the basin scale, those losses are typically less significant because some water is reclaimed and used downstream (Kumar & Ladha, 2011; Li, et al., 2023; Huber et al., 2023).

The traditional flooding system is extremely productive and inhibits weed development, but it requires a large amount of water (Nawaz et al., 2019; Bhatt et al., 2019). It will be necessary to manage non reusable resources carefully in order to combat the effects of climate change on agriculture sector. India will need to take action at every possible level to address how climate change is affecting agricultural and food production (Bhattacharya, 2018; Roy et al., 2024).

2.2.2. Water saving technologies for rice cultivation

The agricultural sector is one of the largest consumers of water but water use in agriculture is often highly inefficient because only a fraction of the water is diverted for plant growth. Whereas the rest is drained or lost through evapotranspiration (ET). The exponential growth of World's population directly demands more food and thus the agricultural requirement of water for irrigation is increasing. Simultaneously, there is less and less water that is of sufficient quality. Thus, the only choice is to produce more while using less water. Water-saving methods in agriculture are becoming increasingly significant and widespread. However, diverse approaches to water conservation include proper irrigation scheduling, effective irrigation practices, and the use of alternate water sources for irrigation. It should be emphasized that enhancing water efficiency frequently brings benefits that go far beyond reduced water consumption.

Irrigation is required when plants cannot meet their water requirements through natural precipitation. Thus, an ideal irrigation effort seeks to cover the difference between a crop's actual water needs and what it can absorb through natural means. It is affected by all meteorological and soil conditions and cultivated plant types. Irrigation practices are important aspects in determining the efficiency and effectiveness of irrigation. Crops have

different daily water requirements and growth periods. Furthermore, crop type has a significant impact on irrigational water requirements. Furthermore, local climate and soil conditions influence crop water availability, often known as physiological dryness. It helps to minimize or lessen occurrences of crop irrigation with too little or too much water. The optimal amount of water is accessible to the plants when they need it due to careful irrigation scheduling that manages the soil reservoir (Shaw et al., 2023).

Rice may be effectively cultivated with less water by utilizing resource conservation technology (Umesh et al., 2017; Bhatt et al., 2019; Ishfaq et al., 2020) and the non-conventional rice cultivation methods help in yield enhancement and water-saving. Several water-saving technologies have been tested and distributed to improve rice output, including (Zhang et al., 2020a):

a. Direct seeded rice (DSR)
b. Alternate wetting and drying (AWD)
c. Aerobic rice
d. System of rice intensification (SRI)
e. Saturated soil culture
f. Raised-bed systems
g. System of ground cover rice
h. Combining shallow water depth with wetting and drying
i. Transplanting in non-puddled soil
j. Non-flooded mulching cultivation
k. Intermittent dry spells
l. Semi-dry cultivation

DSR and AWD are attractive options among water-saving techniques and are practiced in various parts of the globe (Farooq et al., 2011). Nonetheless, because of increased water inputs and fluctuating fertilizer supplies in light-textured soils, DSR and AWD have not proven effective. (Chakraborty et al., 2017). Adoption of mild/ safe-AWD reduces total water inputs while maintaining grain output, whereas severe-AWD reduces total water inputs but reduces yield. Implementing AWD alone is insufficient to maximize benefits; instead, an integrated approach is necessary to improve resource efficiency and overall profitability in the farming industry. These difficulties necessitate site-specific technology and extension work to modify farmer perception, integrated weed management

strategies for weed control, and use of all resources according to soil type and farm condition (Ishfaq et al., 2020). The AWD system has the ability to save 23-33 % of water (Carrijo et al., 2017).

Implementation of water-saving techniques in rice not only enhances paddy output but also promotes carbon sequestration, aids in resource conservation, and reduces greenhouse gas emissions (Yang et al., 2017). Climate scenarios significantly affect rice yield. Even with long-term overfertilization, unfavourable climates will lower yields in the future. The proposed water and carbon management strategy for paddy fields balances water conservation, maintains soil organic carbon (SOC) and steady rice production, and balances water use with the use of adequate organic fertilizer (Jiang et al.,2021).

As a key adaptation strategy to sustain rice production in China, the changing sowing date has been considered. However, it remains unclear to what degree it can lessen the adverse impact of climate change on yield and whether further irrigation is needed. Average yield losses will be effectively compensated when the optimized sowing date is applied. To accomplish these, the rice-sowing date will be extended back by up to 54 days, and an average of 17.8-23.4 % more fresh water will be required in future periods to meet rice growth water requirements. Farmers in Chinese rice production zones will have limited sowing windows by the end of the century as heat events become more frequent. This study reveals that appropriate irrigation and adjustments to sowing dates may alleviate the harmful climate effect on China's rice production (Ding et al., 2020).

Kavitha et al. (2020) studied on SRI technique in India which results in higher grain yield (17 %) coupled with substantial water saving (29 %) resulting in higher Water Use Efficiency (7.7 kg ha^{-1} mm). This approach also benefitted with higher gross income, net profit and benefit cost ratio were also associated. Das et al. (2017) conducted a study on the modified system of rice intensification, Average rice productivity rose by 39 %, while employment and net returns grew by 15 % and 61 %, respectively. Water consumption efficiency improved by 12 %, but water productivity increased by 59 %. In another study higher rice grain yield up to 55 % was obtained with SRI (Nirmala et al., 2021), compared to the conventional transplanting method. The overall cost of producing rice decreased by 22.71 %. (Nirmala et al., 2021). Lowest GHG emissions of 0.280 kg CO_2 e kg^{-1} rice grain. Akondo et al. (2020) and Mishra et al. (2021) also practiced SRI and found better performance in terms of yield-contributing characteristics than conventional

cultivation methods in Bangladesh and Cambodia, Laos, Thailand, and Vietnam respectively.

In an experiment on aerobic rice cultivation in Australia, Silwal et al. (2020) found that a higher leaf area index, fertile spikelets, and immediate water use efficiency during flowering all contributed to an increase in yield. According to Liu et al. (2019), aerobic lowland rice cultivars could produce a higher yield than the upland rice cultivars currently grown under aerobic conditions. The most vulnerable stage of the rice panicle to water stress was the aerobic phase, which caused a significant drop in yield for several kinds. According to Zaman et al. (2018), MR253 rice generated more panicles and more yield when grown in an aerobic environment. In comparison to continuous flooding or any other irrigation regime, rice productivity, water productivity, and N use efficiency were all increased in aerobic systems (de Borja Reis et al., 2018).

The current water-saving irrigation method places a strong emphasis on innovative technology, but the scientific selection of irrigation and drainage modes has been hampered by the lack of research on the possibility of lower output (Sruthi & Surendran, 2023). Although several studies have demonstrated that it is possible to generate good yields while conserving water, farmers lack the necessary information for these methods. A certain amount of yield reduction is possible since several indices, including soil moisture content, soil suction, and other factors, are not properly managed. This is particularly true when determining the lower limit of irrigation. Raising the depth of rainwater after a downpour can lower water consumption under the mode of water storage and controlled irrigation, but it may also result in crop lodging and decreased production (Zhang et al., 2020a).

2.3. Pre and post scenario of the green revolution

After the green revolution, the productivity and yield of crops increased tremendously. This was achieved by replacing the traditional varieties by genetically improved high-yielding and stress-resistant varieties and incorporating synthetic chemicals (fertilizer, pesticide, weedicide etc.). These genetically amended varieties of cereals had 20 % more grain yield than their former cultivars and were more receptive to synthetic chemicals, especially to N fertilizers (Makino, 2021). Additionally, the cropping intensity was also increased to 2-3 cropping seasons per year due to the short crop duration.

For instance, rice cultivars released during the green revolution, IR-8 and IR-72 required 130 days and 100 days to mature, while conventional rice cultivars took 150–180 days (Davies, 2003; Buresh et al., 2021). Consequently, the production of cereals also hiked by 174 % during 1950-1990 whereas the population expanded by 110 % globally (Otero & Pechlaner, 2008; Hossain et al., 2021). Hence, during this period (1960 to1985), the total food production and yield were doubled, and it has had a positive impact on food security and financial stability in many developing nations including India (Conway, 2019) and with the help of green revolution nations enabled to feed their increasing population.

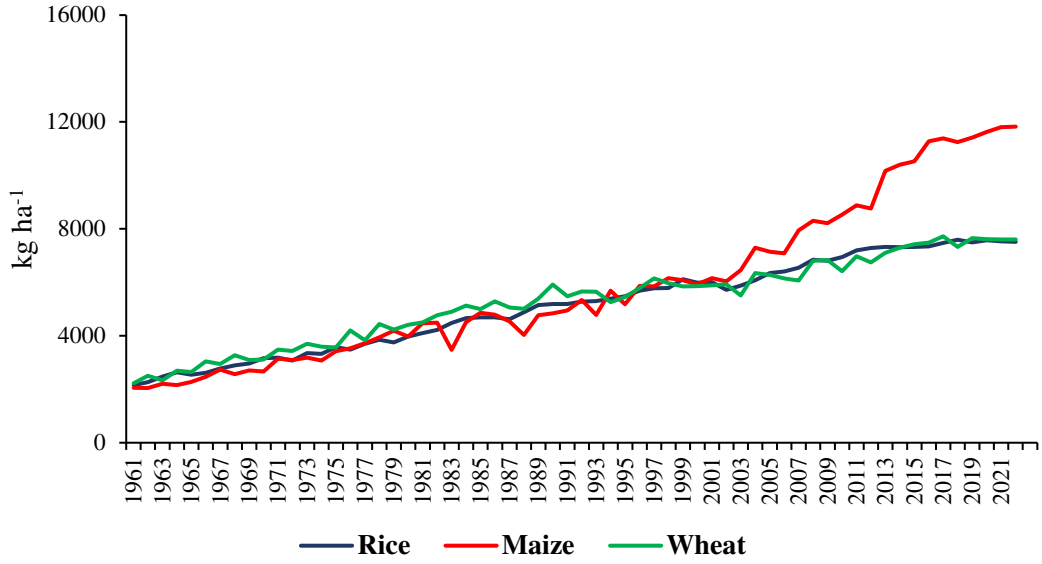


Fig.2.3. World-wide production of rice, maize and wheat

Indian agriculture did not undergo any technological advances in agricultural practices for several millennia before green revolution. The seeds that farmers grew had a genetic makeup that dates back thousands of years. Other technologies used in agriculture included wooden ploughs, waterwheels, and bullock carts, as well as agricultural operations powered by the energy of humans and animals. As a result, post-independence, from 1947 to 1965, the agricultural sector's inability to satisfy India's needs negatively impacted the development of the industrial sector. India was on the edge of a severe famine in the middle of the 1960s due to droughts, a lack of suitable technological advancement, and inadequate land reforms. Thus, such a situation was overcome with the support green revolution (Davies, 2003; Pathak et al., 2022). The usage of high yielding varieties (HYVs) of wheat and rice as well as the adoption of new agricultural practices collectively uplifted the growth rate of food grain output and climbed from 2.4 per cent annually before 1965 to 3.5 per cent after 1965 (FAO, 2019). The practices of using HYV with various chemicals

and machinery together termed "High-yielding variety technology". However, the results of the green revolution reached their maximum efficiency and vigorous usage of fertilizers reduces the fertility of the soil. Hence, World food production reached a point where further improvement is not possible (Fig.2.3) with existing methods. New areas of research and technologies need to be identified to overcome this situation.

2.4. Traditional agronomic research and its limitations

Traditional agronomic research, such as field trials, has been and continues to be a credible source of information for demonstrating causal links between agricultural land management practices and observable measures in the real world (Durr et al., 2016; Liang et al., 2016). Traditional agronomic research methodologies, on the other hand, are becoming insufficient to meet the rate at which data is needed to drive policies and decision-making processes. Old-style agronomic research needs several trials of lab/ pot experiments followed by laborious field experiments. However, these experiments give only the outcomes done at specified times and locations, resulting in season- and site-specific results. Furthermore, these studies are labor-intensive, time-consuming, and costly (Choruma et al., 2019) and induce delays in the data collection period. Again, testing season- and site-specific recommendations for a large variety of factors over several years and on multiple sites is difficult (Hoffmann et al., 2018). In order to summarize a management recommendation for a particular crop for a state/ country, assessing the crop behavior in different agro-ecological zones with the help of on-farm yield trials and multi-location yield trials is needed. But experiments in the field are not always practical. Furthermore, even when and where they are possible, such studies are frequently time and money-consuming. It should be evident that it is difficult to examine every system on Earth to understand the kind of interactions that species have with one another and how these interactions affect community dynamics.

Furthermore, these trails may lack adequate spatial and temporal data to identify appropriate and successful management techniques. Due to the shortcomings of traditional field experiments, there is an urgent need for a tool/ method that allows for the rapid acquisition of new data and research findings, as well as the rapid dissemination of results to end-users in various sectors who rely on such data and results for decision-making. By speeding up these plant–environment processes, the desired outputs and consequences will

be available sooner, reducing the reliance on farm experiments for data (Kephe et al., 2021).

The use of Information and Communication Technologies (ICTs) in agriculture and food has increased in recent years. Many examples are found in the scientific literature: wireless sensor networks used to monitor farms, irrigated areas, or weather conditions (Wang et al., 2006; Delgado et al., 2015; Mekonnen et al., 2019) new hardware and software developments to automate and control agricultural facilities (Voulodimos et al., 2010; Delgado et al., 2015), CSMs, nutrient budgeting models (Surendran et al., 2016) etc. The expansion and penetration of computer/ mobile devices has also led to the development of several model agricultural applications(Molina-Martínez & Ruiz-Canales, 2009; Jonoski et al., 2012; Fuentes et al.,2012; Delgado et al., 2015; Emeana et al., 2020).

Understanding, assessing, and predicting crop yield outcomes under different climate scenarios is critical, as are farm management practices geared toward adaptation and sustainability. As a result, the information necessary for agricultural decision-making at all levels, from farm management to adaptation measures and relief schemes, is increasing, and a mechanism of supplying such information in comparatively shorter time frames is needed (Kepheet al., 2021). Hence, technologies like CSMs must be developed and used effectively to project food crop yield as a function of its abiotic components like soil and climate conditions under diverse scenarios and time frames (Hoogenboom et al., 2015). It is important to note that crop models cannot completely replace field experiments. On the other, there is a growing recognition, particularly among crop modelling experts, that good field trials, despite their scarcity, are critical for improving and testing crop models (Porter et al., 2019). With this in mind, we examine how crop models bridge the gap between traditional field trials and crop models. Scientists and engineers have been evolving more process-oriented simulation models for different crops for more than 40 years. Now in this century CSMs are available for most of the world's major crops. It is an alternative strategy to improve the effectiveness of agronomic experimentation (Kropff et al., 1996; Singh et al., 2005; Divya et al., 2020). With advancements in computer technology and accessibility, they have become a more and more valuable tool for absorbing the knowledge obtained from field research (Bowen et al., 2002). Because the simulation is based on plant and soil processes and their response to diverse environmental circumstances, these models emphasize process-based research (Divya et al., 2020). As a result, the model's output is extrapolative rather than having a site-specific net effect

(Divya et al., 2020). The initial model was developed by De Wit, 1965 by relating the photosynthetic rate of the crop to yield and thereby predicting the yield.

2.5. Evolution of Crop Simulation Models (CSM)

A model is a schematic representation of a system's conception, an act of mimicry, or a set of equations that reflect the behavior of a system, with the goal of assisting, understanding, and enhancing the system's performance (Ahmad & Mahdi, 2019; Abimbola et al., 2022) and a crop model is a computer-based programme which simulates crop development as a function of crop management variables, soil, and weather by using simplified representations of physical processes and predicts crop yield (Fig.2.4). Crop production is the collection of individual plant species grown in a given area to attain an irreversible rise in the development, size, and volume of seeds or consumables from these plants, which are harvested for a variety of reasons. Finally, breeders can predict future needs based on climate change by recreating the characteristics of the natural environmental system investigated on a shorter time scale with an appropriate model (O. Rauff & Bello, 2015).

Crop models have been proven to be significant decision-making tools for assessing the effects of climate change and management methods on the productivity and environmental performance of different cropping systems, promoting better and more sustainable agriculture (Kephe et al., 2021) (Fig.2.5). These models can help you save time and money. The prediction accuracy of simulation models is a critical component in the decision-making process. CSMs are useful not only for predicting yield but also for quantitative analysis. They also provide an opportunity to investigate cultivar performance in new location before going for time-consuming and costly field experiments. Long and costly agronomic and modelling field studies with a large number of treatments and combinations could be pre-evaluated in seconds using tests on a desktop computer or laptop. They offer a cheaper and quicker way to explore the effects of agricultural land management strategies on crop production and the environment. (Choruma et al., 2019; Kephe et al., 2021) and demonstrate the best level of management for achieving economically efficient yields (Kadiyala et al., 2015a).

Soil, atmosphere, and plants that dwell in it interact in a complex way to form the bio-system. A change in one element might have both positive and negative consequences. The farmer's primary goal is to minimize the undesired while achieving the desired result.

Among the various modelling methodologies, mathematical modelling allows one to forecast design behaviors while keeping costs to a minimum. Agricultural systems are essentially modified ecosystems that are extremely difficult to manage. Over the years, various sorts of models have been developed.

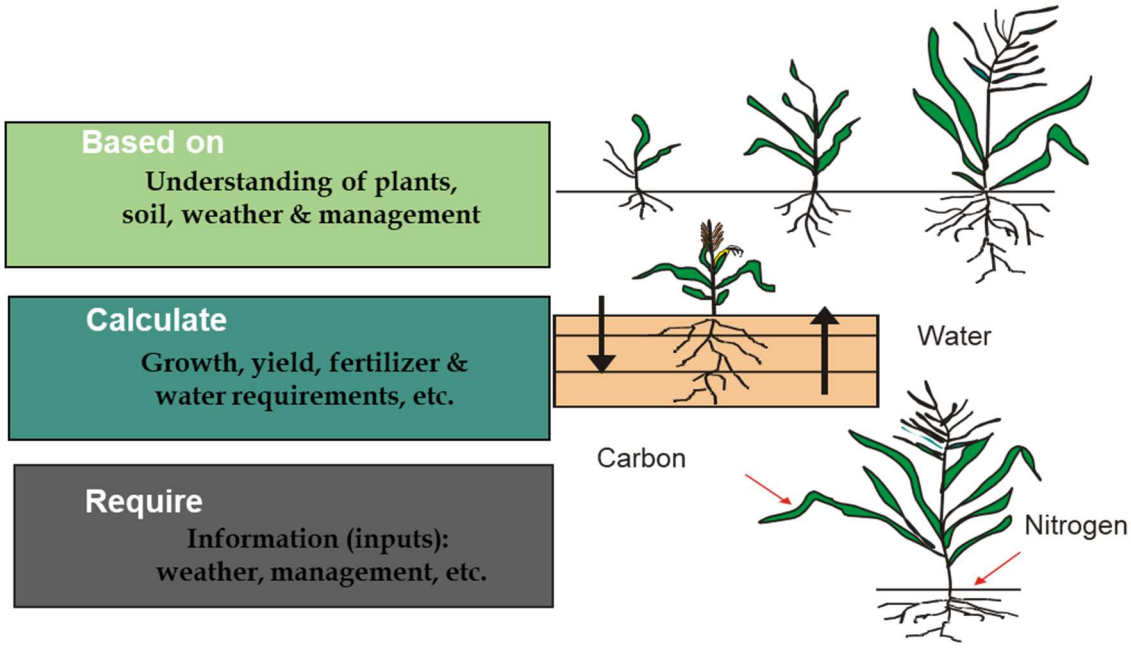


Fig.2.4. Graphical representation of Crop Simulation Models

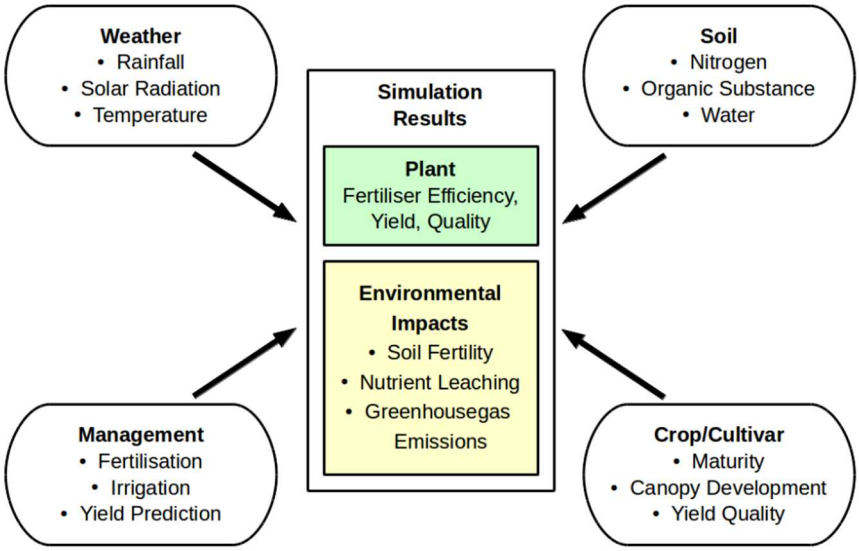


Fig.2.5. Working of Crop Simulation Models

They can be divided into a number of categories or sorts, ranging from explanatory models to empirical ones, according to their functional components and prediction systems (Hoogenboom, 1999). In empirical models, the assessment of yield is based on direct descriptions of observable data that are represented as regression equations. Data are analysed using an empirical approach, and then an equation or set of equations are fitted to the data. The mechanisms that regulate the outputs are not disclosed in these models (Arvidsson & Håkansson, 1991; Phakamas et al., 2013). Mechanistic models, on the other hand, describe both the correlations between meteorological variables and crop yields as well as the mechanisms governing these interactions (Bannayan et al., 2003). Each outcome in stochastic models has a probability element associated with it. Different outputs are provided along with probability for each combination of inputs. These models specify the rate-dependent state of the model variables (Etkin et al., 2015). Quantitative descriptions of the mechanisms behind a behavior make up explanatory models. Such models quantify each component separately before integrating them into the overall system (Hoogenboom, 1999). The most commonly used models are the Environmental Policy Integrated Climate (EPIC) model (Williams, 1990; Khan & Walker, 2015), CERES-maize (Bao et al., 2017), PM Models (Boylan & Russell, 2006), CROPGRO, Decision Support System for Agro-Technology Transfer (DSSAT) model (Ritchie & Otter-Nacke, 1985; Jones et al., 1998; Jones et al., 2003; Boote et al., 2010; Hoogenboom et al., 2015), SALUS (Basso and Ritchie, 2015; Dzotsi et al., 2013) SORGF (Wiegand and Richardson, 1984), APSIM- Agriculture Production Systems Simulator (Keating et al., 2003a, 2003b; Holzworth et al., 2014), CERES-pearl millet model (Santos et al., 2016), CROPSYST (Stöckle et al., 2003, 2014), CROPWAT (Smith, 1992; FAO, 2009), STICS (Brisson et al., 2003; Bergez et al., 2014). These CSMs can incorporate soil physicochemical properties, water, N, carbon, and phosphorus, and some models are able to include pests and damage to some crops (Batchelor et al., 1993). Most models have been built for specific crops and places, and they are not necessarily relevant to other regions. (Adejuwon, 2005; Khan & Walker, 2015). Thus, it is necessary to assess the crop models' applicability before introducing them to new areas.

2.6. Crop Simulation Models used in agriculture

Crop modelling has mostly been utilized as a decision-making tool for crop management in conjunction with the environment and crop physiology. Given that crop

development is impacted by environmental factors and crop management, it can be a useful tool for management decisions aimed at improving yield. The application of CSM has been widespread in many areas of agriculture, including generating optimum management practices for maximizing output, responding to shifting climatic circumstances, identifying pest management techniques, etc. This chapter covers the review of literature based on the study that has been carried out.

Planet Earth supports a wide range of life forms, from single-celled microbes to complex living beings and offers the necessary resources and products to create an ecosystem capable of supporting the lives in it. Air, water, and soil are the major components required for continuing life on earth. Any changes that occur in these systems will directly influence the balance of life on earth. The earth and its climate kept on changing from its origin and moulded itself suitable for life. These changes happened at a very slow pace and took several thousand years. But now, different anthropogenic actions accelerate climate change which threatens the entire ecosystem. In addition to this, the ever-increasing population and its food demand worsen the situation. Hence, natural resources that are essential for food production, such as crops, water, and nutrients, are now under pressure (Ungureanu et al., 2020). Hence, more cautious efforts are needed in the utilization of natural resources for us and for the future.

The world's population is projected to rise by 2 billion people in the next 30 years, i.e., from 7.7 billion to 9.7 billion people on the planet in 2050 (UN DESA, 2022). Hence, the need for clean water and food leads to the concepts of food and water security. Since agriculture is a significant freshwater user, these cropping systems must make optimal use of the available water and other resources. Therefore, it is crucial to identify the new practices and technologies that might increase water and nutrient usage efficiency, lead to large water and other natural resource savings, and thus increase yield.

2.6.1. Importance of CSM

CSMs are significant in agricultural resource management and have been used for over four decades to study, observe, and experiment with crop systems (Graves et al., 2002; Nagamani & Mariappan, 2017). Crop growth simulation models are used to study the links between environmental and crop productivity parameters (Adejuwon, 2005; Gul et al., 2020). These models employ one or more arrays of differential equations throughout

time, typically from planting to harvest, to estimate agricultural productivity as a function of weather, soil conditions, and crop management (Murthy, 2004). The 1970s saw the introduction of crop models and their usage in agriculture, but practitioners with varying degrees of exposure and experience can now access a wider variety of models (Cheeroo-Nayamuth et al., 2000). CSMs can also be utilized as DSS to evaluate the economic and risk consequences of agricultural managing practices. According to Zhao et al. (2016), if the models are validated using credible observed field data, the modelling approach can yield reasonably credible results for developing agricultural land management strategies (fig.2.6). They are critical for forecasts because they may incorporate knowledge about specific crop physiology gathered from years of laboratory and field trials, as well as provide an effective method of evaluating crop responses to climate change and different management scenarios. They are modules built for specific crops within each model (Kephe et al., 2021).

Each model contains modules designed for a particular crop; these modules can incorporate knowledge of a crop's physiology gathered over many years from field and laboratory experiments. They also offer a useful way to look into how crops are responding to climate change and different management scenarios; these modules are crucial for projections (Kephe, et al., 2021).

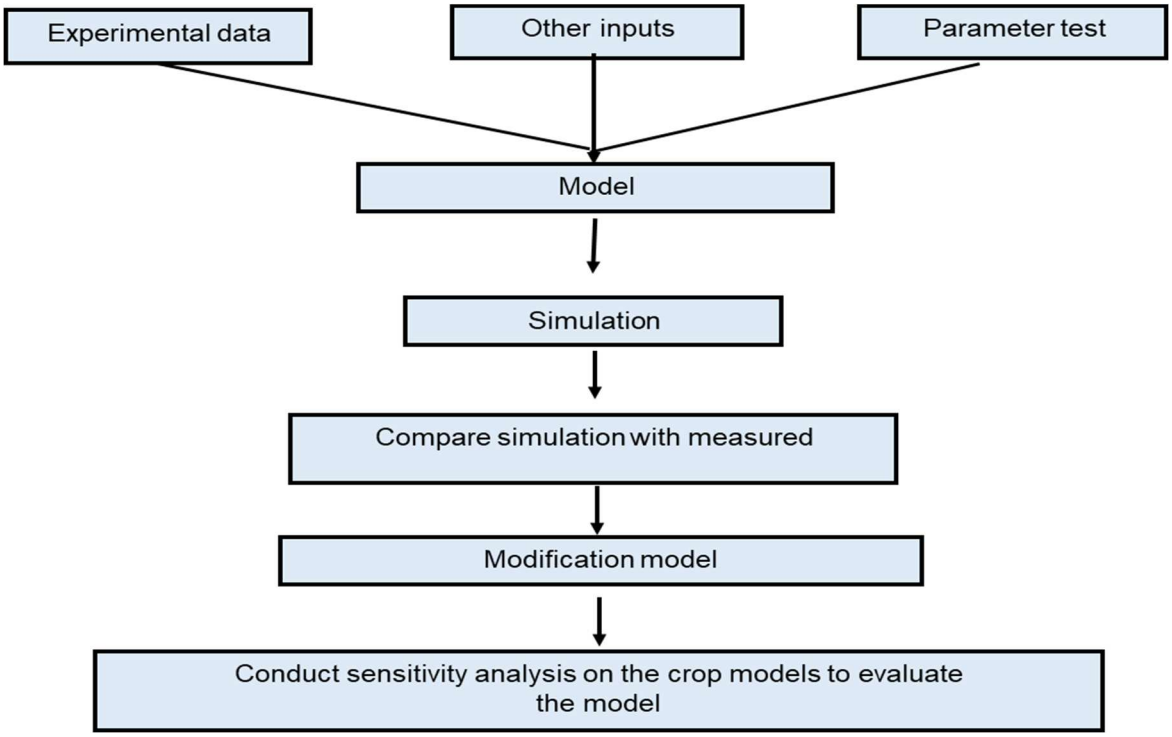


Fig.2.6. Calibration and Validation of Crop simulation model

2.6.2. Crop Simulation Models used for water and nutrient management and recent progress

Crop growth and physiological processes are negatively impacted by water and nutrient deficiency during the crop growth phase (Hsiao, 1973), which decreases yield (Osakabe et al., 2014). For the proper development of crops, proper nutrition irrigation management and scientific scheduling are necessary, and simulation models can aid with this (Boggess & Amerling, 1983). Crop growth models are created to solve crop yield and economic variation problems in agriculture. Researchers were able to integrate different approaches to finding explanations to the multifaceted problem of water, nutrient, soil, environment and crop management when farmers faced the difficult task of managing their crops with limited water and poor soils in harsh and risky climates. Crop water and nutrient demand are influenced by a variety of factors, including climatic conditions, topography, lithology, soil, management practices, crop type, and so on (Rauff & Bello, 2015). Knowing these parameters allows for the estimation of crop-nutrient-water requirements and the establishment of best management practices. This allows researchers to comprehend the biological behavior of Plants under various situations and to implement effective management under these conditions to achieve the borderline yield.

Agricultural crop water and nutrient requirements can be determined locally at the field level through site-specific management. In agricultural research, crop models are used to test scientific hypotheses, highlight information gaps, organize data, and integrate across various disciplines. CSMs can be used to forecast plant performance in areas where the plant has never been grown before or in areas where the crop has not been grown under ideal conditions (Murthy, 2004). Such applications are beneficial to regional development and agricultural planning in nations with limited resources. It can be built with varying degrees of intricacy. The goal of the modelling exercise determines the level of complexity required (Chapman et al., 1993; Matthews et al., 2002; Tittonell et al., 2010). For models aimed at yield prediction and model improvement, the top-down approach to model design is appropriate.

The integration of a number of unrelated and opposing factors is necessary for decision-making. In the past ten years, decision support system (DSS) technologies have been developed to helping the decision-making process using the data through models to solve various problems, as well as with environmental and climate change decisions. These tools for making decisions assist the decision-maker in outlining all of the potential

possibilities. DSS is widely used in India for agricultural management, particularly in crop productivity. The Crop Environment Resource Synthesis (CERES) – Wheat DSS was used to simulate wheat growth in Punjab, revealing that soil water-holding capacity affects grain yield and water productivity. The Cropping System Model "DSSAT-CSMCERES-Wheat 4.0" was used to predict crop yield and irrigation scheduling.

Abimbola et al. (2022) conducted an experiment using a Hybrid-Maize model for different combinations of irrigation and N nutrient management practices during 2019 and 2020. The maize variety used in this experiment was 1197-AMT. Calibrated models showed the relationship between total received water and other six parameters which were more sensitive to yields, namely, light use efficiency, maximum photosynthetic rate, potential kernel filling rate, number of kernels per ear growth respiration coefficient of grain, and observed parameter identifying the relative influence of a soil layer to uptake of water. This was a novel multi-parameter approach for yield improvement which was coupled with real-time information. This calibrated Hybrid-Maize model can be used for yield prediction of management of in-season season.

Araya et al. (2021) used the DSSAT to model the effects of cropping systems and water management strategies on the production of various crops. For five years, the treatments involved combining various cropping (wheat, barley, and chickpea) systems and water management techniques. Calculations were made for the yield gaps, relative yields, and yield variations. This case study simulation demonstrated the significance of combining crop rotations with water and soil conservation techniques to increase overall yields and make contributions to ecological intensification.

Mao et al. (2005) found spatial patterns in crop yield, water use, and water use related to water management with SVAT-crop growth model. Wu et al. (2006, 2008) simulated climate effects on grain yield and water demand using WOFOST model. Yang et al. (2006) proposed methods for increasing yield with minimal irrigation water using DSSAT- Wheat model and Chen et al. (2010) studied water resource efficiency and sustainable utilization in China using APSIM model (Chen et al., 2010).

The relatively recent method of nutrient recommendations is based mostly on the crop's nutrient requirement to attain the target yield and the soil's natural nutrient supply. The SITE-SPECIFIC NUTRIENT MANAGEMENT (SSNM) recommendations could be developed solely or in conjunction with soil and plant analysis. According to Dass et al.

(2014), SSNM technologies and tools can improve nitrogen use efficiency, crop production, and crop profitability in addition to improving farm lives. APSIM, COUP, CERES, EPIC, CROPSYST, HERMES, DAISY, FASSET, WOFOST, MONICA, and STICS and are the popular CSMs used in nutrient management. The ability of APSIM model to forecast nutrient availability and subsequent crop growth after the addition of organic and inorganic sources of N and P was assessed by Probert and Dimes in 2004. A collection of biophysical modules in the APSIM modelling framework can be customized to simulate biological and physical processes in agricultural systems.

Adiele et al.'s (2022) experiment aimed to construct and evaluate the crop model LINTUL-Cassava-capacity NPK's to imitate cassava biomass growth and yield under nutrient-limited conditions. In Nigeria, research data were collected throughout two successive growing seasons between 2016 and 2018 from several agro-ecologies. Combining the NPK - nutrition indices allowed for the implementation of nutrient stress in the model. Demand and supply of nutrient equivalents were then balanced to determine nutrient uptake. This is the first tried-and-true model of the cassava process-based three macronutrients. This study deepens our understanding of N, P, and K interactions on cassava growth and production as well as nutrient restrictions.

GOSSYM was CSM used by Landivar et al. (1983) to examine the yield differences between cotton plants with deeply lobed (okra-leaf) leaves and cotton plants with regular leaves under various irrigation and N fertilization conditions. Cotton with okra leaves often generate more fruiting sites than cotton with regular leaves. The model's results indicated that cotton genotypes with smaller leaves would utilize the extra carbohydrates for the growth of roots, stems, and flowers instead of increasing their leaf area.

A comprehensive literature search was conducted in the Science Direct, Google Scholar, PubMed and Web of Knowledge databases using the keywords ‘Crop simulation models for water and nutrient management’ for a span of the last 10 years. The study was chosen based on the criteria that the field experiments in water and nutrient management conducted over the last few decades using CSM have been undertaken in a suitable scientific manner. There were 20 articles that fit this criterion. (Table 2.1). These field trials were mostly conducted in India, Pakistan, USA, China, Pakistan and European countries. Most of the references focused on rice, wheat, maize, pea, potato, soyabean, sunflower and sorghum.

Table 2.1. Summary of different studies on water and nutrient management using crop simulation model

Sl. No.	Model	Crop	Country	Output	Reference
Water management					
1	CERES-Rice	Rice	Pakistan	Developed new irrigation regime with highest yield	Ahmad et al., 2013a
2	SUBSTOR-POTATO	potatoes	Spain	Most suitable irrigation strategy in semi-arid regions	Montoya et al., 2019
3	AquaCrop	potatoes	Denmark.	Irrigation scheduling in potato production	Razzaghi et al., 2017
4	CSCER047 – barley	wheat, barley, chickpea	Ethiopia	Crop rotations with soil and water conservation practices for improving overall yields and ecological intensification.	Araya et al., 2021
5	CSM–CERES–Maize	Maize	Colorado	Model using the FAO-56 PM technique performed better in terms of grain yield.	Anothai et al., 2013
6	CSM-CROPGRO	Peanut	Georgia	Simulate the development of peanuts, as well as soil water content, for various irrigation regimes.	Tojo Soler et al., 2013
7	CROPGRO- cotton	cotton	Australia	Maximum profit and yield are different, which has economic and environmental implications.	Cammarano et al., 2012
8	CERES rice	Rice	Iran	Model is calibrated and validated to predict for irrigation and different densities conditions in northern Iran	Ebrahimirad et al., 2018

Nutrient management					
9	CSM-IXIM- maize	Maize	Indonesia, Philippine, Vietnam	Agronomic n efficiency increased by 42 %; site-specific nutrient management	Pasuquin et al., 2014
10	EPIC	Rice, Wheat, Maize	China	Bmp across different regions, cropping systems and weather conditions of China	Zhang et al., 2018
11	CERES-Rice	Rice	India	15 % more yield and 25 % less no3 – leaching	Prasad & Mailapalli, 2017
12	APSIM	potatoes	Australia	Prediction of yield, phenology, nutrient uptake and nutrient leaching	Borus et al., 2018
13	CSM-CERES-Maize	Maize	China	Simulate soil N dynamics and predict soil organic carbon sequestration	Yang et al., 2013
14	OILCROP-SUN	Sunflower	Pakistan	Identify the optimum management practices for a specific region	Ahmad et al., 2013b
15	DSSAT-CSM	Wheat and Maize	China	Sensitivity analysis simulated grain yields to fertilizer n application rates under various soil water conditions	Li et al., 2015
16	CERES-Rice	Rice	Pakistan	Predicted high yield and monitory return of irrigated rice in the semiarid environment	Ahmad et al., 2011
Water and Nutrient management					
18	CERES-Rice	Rice, Maize	India	Best management practices for aerobic rice and maize	Kadiyala et al., 2015b
19	CERES rice	Rice	Iran	Model calibrated and validated to predict the experimental results of irrigation and N conditions in northern Iran	Amiri et al., 2013

2.6.3. DSS tools

The majority of DSS tools currently in use are relatively specific to specific situations, such as when to apply a fungicide to a specific crop, when to apply the next irrigation, or how much nitrogen fertilizer to apply to a specific crop in a specific location. (Jones et al., 2017). In the management of water resources, numerous DSSs have been created for irrigation scheduling of field crops. Numerous DSSs have been created in the USA by private consultancy firms (Cahn & Johnson, 2017; Montoro et al., 2011). CROPWAT (Smith, 1992), created by the FAO to determine the crop water requirements of multiple crop species, for various management situations, is one well-known and well-established DSS for irrigation scheduling. The FAO-developed crop growth model AQUACROP (Steduto et al., 2009) predicts the yield response to water supply for field crops (Li et al., 2018).

The CER (a consortium of irrigation administrators) in the Emilia-Romagna region of Italy runs the web service IRRINET (Mannini et al., 2013; Gallardo et al., 2020), which offers irrigation advice for crops of numerous vegetable species utilizing the water balance. The Irrigation-Advisor DSS (Mirás-Avalos, 2019), which is based on weather forecasts and has recently been successfully developed for vegetable crops in the Mediterranean coast of Spain, is able to separately assess soil evaporation and crop transpiration. For the control of sprinkler irrigation of approximately 27 vegetable crops in Central Europe, the Gesenheim Irrigation Scheduling was developed in Germany (Olberz et al., 2018). IRRINET, ISS-ITAP, Irrigation advisor, IRRIX, GSEHEN, ProHo, Hydrotech are the most relevant DSSs for irrigation management of different vegetable crops and fruit trees

In order to help in nutrient (N) management of vegetable crops, a number of DSSs based on simulation models have been used in Europe, including N-Expert (Feller et al., 2011, 2015) and Azofert are DSS tools that recommend N levels (Machet et al., 2017). N-Expert, CAL-FERT program (Incrocci et al., 2013), FertiliCalc (Villalobos et al., 2020), and PLANET are DSS that determine fertilization schedules for N, P, and K for diverse vegetable species. Recommendations for N are based on anticipated yield and consider soil N supply. DSSs presently used that can determine the crop nutrient and irrigation needs for fertigated vegetable crops are VegSyst, GesCoN, FERTIRRIGERE V2.11, and CROPMANAGE.

IRRIX DSS (Casadesús et al., 2012) and Hydro-Tech (Todorovic et al., 2016) are irrigation scheduling DSSs in combination with soil and plant sensors. The Spanish DSS, Irrigation-Advisor (Ramirez-Cuesta et al., 2018) and Australia-made IrriSAT (Car et al., 2012) are remote-sensing based irrigation management technologies. To establish the analyses and outputs to address questions about the management of that specific farm's biophysical and socioeconomic situation, as well as the uncertainties in those estimates, we create a possible DSS platform that connects various models, databases, analysis, and information synthesis tools in a user-friendly interface.

2.7. Crop simulation models used for Rice: special emphasis on DSSAT

International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) developed a Decision Support System for Agrotechnology Transfer (DSSAT) with an international network of scientists to enable the use of crop models in a system. The first version of DSSAT was released in 1989 it is a group of separate applications that work together. The development of DSSAT was initially motivated by the requirement to integrate information on soil, weather crops and management for making better decisions in transferring production technology from one region to other regions with different soil and climatic conditions (IBSNAT, 1993). This Software assists users in creating databases, comparing simulation results with observations, and deciding whether to make changes to the models in order to increase accuracy (Uehara, 1989; Jones et al., 1998). Additionally, tools included in DSSAT enable users to simulate crop management alternatives across several years to evaluate the hazards related to each option (Jones et al., 2003). The current DSSAT version is 4.6.1, which includes models of 20 crops drawn from the former DSSAT CROPGRO and CERES models. Numerous models have been created to predict rice growth, including the ORYZA1 model developed by Kropff et al. (1994), DSSAT CERES-Rice model designed by Singh et al. (1993), SIMRIW model developed by Horie et al. (1992), TRYM by Williams et al. (1994), VSM by Kobayashi (1994), RICAM by Qi et al. (1993), a model to predict rice-weed competition by Graf et al.(1990) and InfoCrop model by Aggarwal et al., 2006a, b. Each model has a unique set of underlying assumptions and complexity due to its unique objective(s). ORYZA2000 and CERES-Rice are the popularly used crop models for rice.

The APSIM model was designed to mimic different crop sequences, residue/ tillage techniques, and field management strategies (Keating et al., 2003a). Because of its roots

in dryland cropping applications, it was previously unable to replicate processes associated with the long-term flooded or saturated soil conditions found in rice-based systems. To overcome this problem, the rice crop components of the ORYZA2000 rice model were added, and the APSIM soil water and nutrient modules were updated to include descriptions of SOC and N dynamics under anaerobic circumstances. An eco-physiological model known as ORYZA2000 can simulate rice growth and development for a specified yield using different N fertilizer rates and planting density in a rice production system. This model can be used explore the impacts of rice genotype, N management, and their interactions on yield for optimal crop management (Yuan et al., 2017).

The WARM rice model is utilized within the agricultural yield forecasting system of the European Commission. The model is appropriate for forecasting rice yields on regional, national, and international scales due to WARM's resilience and accuracy, low input requirements, and implementation of modules for simulating biophysical phenomena that greatly influence the year-to-year yield variance.

The DSSAT system includes the CERES-Rice generic and dynamic simulation model (Godwin & Jones, 1991; Singh, 1994; Hoogenboom et al., 1995; Godwin & Singh, 1998; Ritchie et al., 1998; Jones et al., 2003). It includes a thorough explanation of crop growth in ideal, nitrogen- and water-limited circumstances. Despite only being partially explained in many papers, the concept is relatively popular (Timsina & Humphreys, 2003). Typically, experimental data from many sites or from more than one season were used just once to calibrate and evaluate CERES-rice. Model evaluations typically do not include any or very few quantitative goodness-of-fit factors and are instead restricted to graphical comparisons of simulated and measured crop growth characteristics (Bouman & van Laar, 2006).

2.7.1. Crop simulation models used for rice yield

Busato (2015) determined the essential group of input variables and verified the simulation model (IDEF3 modelling scheme). The operational parameter prediction error was determined to be extremely low, ranging from 2.59 % to 3.12 %, based on measurements collected during validation. When compared to the actual practice of harvesting a full operating width, the simulated model practiced selective harvesting at a reduced operating width. It was discovered that harvesting at a smaller operational width

greatly boosted capacity (up to 7 %), especially when the system performance was constrained by the capacity of the available transport units. Su et al. (2017) integrated developmental stage and yield prediction methods to create a support vector machine-based open crop model (SBOCM) for rice. Models could predict the rice yield and developmental stage for perennial simulation and one-year rice predictions within its limits, while not being a crop physiology simulation model. Future integration with significant social and economic elements has the potential to increase prediction precision and applicability.

Using long-term (more than 30 years) meteorological data, Yin & Struik (2017) examined the crop model GECROS for rice in tropical, subtropical, and temperate regions to assess several biochemical factors for yield enhancement. All biochemical techniques benefited crop mass production and were higher in the presence than in the absence of drought, and under the current climate than in the climate forecasted for 2050.

Gumel's (2017) study used the Ceres rice model v4.6.1.0 to study the seasonal impact of temperature and rainfall on rice yield. The model accurately predicted rice yield with an RMSPE of 8.9 % and a D- Index of 0.99. The study found that temperature increases led to a loss in yield, while rainfall variations had both positive and negative effects

The findings of the Jha et al. (2019) study show that averaging the simulated yield using individual members does not ensure superior yield prediction, in contrast to the traditional ensemble averaging strategy frequently employed in seasonal climate forecasting. The study utilized the Cropping System Model-CERES-Rice and 28 years' worth of daily hindcasts from the coupled forecast system model version 2 (CFSv2) SPS. Li et al. (2020) assessed the rice yield with CERES-Rice and ORYZA crop models for two widely grown varieties using a 34-year database in the Mississippi Delta region. Because ORYZA used lower cardinal temperatures, CERES-Rice more accurately predicted the length of growth than that model did. The accuracy of ORYZA was enhanced and systematic error was decreased with a rise in base and ideal temperatures. Following that, both models performed similarly when it came to estimating the length of the growing season and the production of rice for most locations and years. Although CERES-Rice projections were more responsive to years with reduced solar energy, neither model was especially good at simulating the detrimental effects of extreme heat or cold. According to

these findings, both models can be used to investigate the typical response of various rice cultivars in the Mississippi Delta region for decision-support studies incorporating the current climate scenarios.

The genetic coefficients for rice were calibrated and evaluated by Phakamas et al. (2013) for Thailand. The new coefficient values can be used to calculate solar radiation from air temperature data for all sites in Thailand and other Southeast Asian environments with similar climates and successfully used to yield predictions. Jha et al. (2022) estimated genetic coefficients of two rice genotypes in the Philippines, namely, inbred PSB Rc82 and hybrid Mestizo 20, for the model CERES-Rice for predicting best phenology and yield, using parameter estimation methods such as Genotype Coefficient Calculator Generalized Likelihood Uncertainty Estimation, and National Microcomputer Genetic Association) (Noisy Monte Carlo Genetic Algorithm. When a crop model is used to test the performance of a new rice cultivar, it is critical to estimate its genetic coefficients.

2.7.2. Crop simulation models used for water management in rice crop

Water shortage in many rice-growing locations, combined with rising global food production demands, is driving research into enhanced water usage efficiency and modified agricultural techniques in rice-based cropping systems. Cropping system models that have been thoroughly validated and reflect interactions between soil water and nutrient dynamics, crop growth, climate, and management can help in the evaluation of innovative agricultural practices.

Confalonieri & Bocch (2005) calibrated and validated the CropSyst model for rice growth in Northern Italy from 1989 to 2002 under flooded conditions. The model improved yields by considering the thermal profile, which is strongly influenced by flooding water at mid-latitudes. Confalonier et al. (2009) evaluated the WARM model for rice growth simulation in China and Italy, demonstrating its robustness. Gaydon et al. (2012) improved the APSIM model against various rice-based cropping systems, soil types, management practices, crop species, varieties, and sequences. Maniruzzaman et al. (2015) calibrated and validated the AquaCrop model for rice crop growth modelling under different irrigation water regimes at the Bangladesh Rice Research Institute. The FAO AquaCrop model was able to forecast rice growth and yield with acceptable accuracy under varied water regimes. The CERES-Rice model was calibrated by Ebrahimirad et al. (2018) in Iran's semi-Mediterranean climate during the 2014 and 2015 cropping seasons

under various densities and water management choices. In both calibration and evaluation, the observed and anticipated planting densities for rice exhibited good agreement.

Akinbile et al. (2020) used CROPWAT to estimate crop water requirements and AQUACROP and CERES models were calibrated and validated for upland rice's response to various irrigation schedules in Nigeria for two seasons 2015 and 2016. Five different ET treatments were used on NERICA 4. Results revealed that when grain and biomass yields were simulated about irrigation schedules, there were substantial discrepancies between the models. While both CERES and AQUACROP somewhat overestimated grains and biomass yields, CERES slightly underestimated the leaf area index (LAI). While CERES had the highest grain yield accuracy, AQUACROP had the highest biomass yield accuracy and slightly overestimated canopy cover, making it a useful tool for calculating water needs and ET. In the simulation of rice grain and biomass yield, the models demonstrated great performance and accuracy.

With experimental data collected over a ten-year period (2006–2015) at the CIMMYT–BISA (Borlaug Institute for South Asia) research farm in Pusa, Bihar, Jha et al. (2020) calibrated and validated the DSSAT CERES–Rice model and developed genetic coefficients for the Rajendra Mahsuri rice variety. The goal of the study is to determine the effects of water stress on crop productivity and the optimal management practices to increase rice yield. The model showed that water stress reduced rice yield by 24 %, 33 %, and 43 %, respectively, during the vegetative, mature, and reproductive phases. Several optimum management strategies like transplanting date (June), crop row spacing (15-25 cm), crop residue application rate (2500 kg ha^{-1}), and planting depth (2–4 cm) were identified for the highest yield.

2.7.3. Crop simulation models used for nutrient management in rice crop

Aggarwal et al. (1997) used the ORYZA-1 model to investigate the yield potential of IR72 (check cultivar) with three levels of N management: Agronomic recommendations for high yield potential, as well as growth-rate-driven N uptake, were implemented in breeder screening plots. The results showed that the cultivar has a high yield potential that can be enhanced with better N management and less yield for the level of management that breeders typically use. As a result, even if genotypes have higher yield potential traits, they will be unable to express them due to poor nutrient management.

Swain et al. (2007) calibrated and evaluated the CERES–Rice model for cultivar IR 36 cultivated at Cuttack, Orissa. He predicted the phenological events accurately and simulated yield at various levels of N and found it in close agreement with actual yield. By using field experimental data from Kharagpur, India, Swain & Yadav (2009) calibrated and thoroughly evaluated the crop simulation model CERES-rice for medium and long-duration varieties. The CERES-Rice model predicted increased yield variability for the Swarna variety compared to the IR-36 and Lalat verities under rainfed conditions in Kharagpur, India, using the past 27 years (1974–2000) of weather data. Under ideal water and nutrient conditions, rice grain production rose by up to 6 % with a 100ppm increase in atmospheric CO_2. The yield of the IR 36 and Lalat types decreased with a 20 °C increase in average air temperature, but the yield of the long-lasting variety increased. However, under ideal input management conditions, the variety Swarna with superior climate change tolerance than the medium duration varieties had the best mean yield.

For evaluating the impact of N fertilizer rates and split N fertilizer application on rice yields grown in paddy fields that were irrigated with reclaimed wastewater, Jeong et al. (2014) calibrated and validated the DSSAT model in Suwon, Gyeonggi-do, central Korea. According to the findings, the ideal N fertilizer rate for paddy fields of rice that are irrigated with reclaimed wastewater is thought to be 20 to 50 per cent less than the typical fertilizer rate (SFR). It was shown that changing the split N fertilizer application rate was sufficient to produce the desired rice yield and reduced the amount of N fertilizer needed by an extra 10 to 20 kg ha^{-1}.

Yuan et al. (2017) calibrated ORYZA (v3) model to simulate yields under different N rates, planting densities, dynamics of crop biomass, leaf area index seasonal yield, and seedlings per hill, using historical weather data from 1986 to 2015 but slightly over-estimated leaf N concentration. Gaydon et al. (2012) simulated the CERES-Rice model to sustain soil organic C and soil N-supplying capability in rice-based cropping systems. It is demonstrated that the performance of simulations of long-term rice cropping systems with and without the inclusion of organic inputs differs significantly, and this helps explore sustainability concerns related to management change in rice-based cropping systems.

2.7.4. Crop simulation models used for water and nutrient managements in rice crop

Rice growth and development are simulated by Bouman & van Laar (2006) using the ORYZA2000 model for water and N management. Lowland rice's growth and

development are simulated using ORYZA2000 (Bouman et al., 1996) for potential production, water, and N restrictions. It is evaluated that the crop is well protected from pests, diseases, and weeds in each of these production scenarios and that yields are not affected. In Bouman & van Laar (2006), data collection of five field tests with irrigated rice was conducted at IRRI between 1991 and 1993. Even though the simulated LAI exceeded the measured values, particularly at low N application levels, ORYZA2000 can be utilized in the field of N fertilizer studies and to research the best N application regimes. Future model upgrades will draw on the generated database and quantitative goodness-of-fit parameters.

Ahmad et al. (2011) evaluated CERES-Rice's ability to simulate the growth and development of Basmati-385 rice under irrigated conditions in Pakistan. They conducted field trials from 2000-2001, analyzing 52 scenarios using historical weather data. The model was found to replicate rice growth and production with an average error of 11 % between simulated and observed yield. This strategy has proven to be an efficient way to manage N and optimize density for high yield and financial return. It will support the production of rice.

Amiri et al. (2013) evaluated the CERES rice model under various N and water regimes in northern Iran during 2005- 2007. Results showed that predictions were in good agreement with observed yields, total dry matter yields and N uptake. The CERES rice model can be used in northern Iranian environments for studies on nitrogen and irrigation (Darikandeh et al., 2023).

The root zone modelling approach and simulation with the HYDRUS-1D model were used by Lama et al. (2014) to assess the potential recharge and nitrate leaching below the root zone of rice crops. According to the verified results, 55.5 % of the applied water percolated beneath the root zone. Volatilization, denitrification, plant uptake, and leaching losses in the 120 cm deep soil profile were calculated as 24.0, 18.9, 109.0, and 28.5 kg N ha^{-1}, respectively. Nitrate discharge was equal to 23.7 % of additional fertilizer. Different fertilizer application rates over the recommended dose were used to create various nitrate leaching scenarios. The assessment of nitrate leaching under the root zone under various fertilizer input situations for rice cultivated in similar hydroagro-climatic zones may be done using these scenarios, which revealed an increasing tendency with increasing fertilizer rates.

Using the DSSATCERES-Rice model, Alejo (2020) evaluated the effects of climate change on aerobic rice production. For calibration and validation, actual data from four cropping seasons at two sites were used. Results demonstrated that DSSAT-CERES-Rice was capable of simulating aerobic rice production accurately. Rice output was negatively impacted by changes in seasonal rainfall and temperature, particularly during dry seasons. By the end of the twenty-first century, crop improvements could drop from 83 % to 53 % and yield declines could rise from 150 % to 177 % as a result of climate change. A variety of aerobic rice farm crop and nutrient management strategies, as well as other climatic and soil variables, might be evaluated using the obtained set of genetic coefficients. The long-term projections for aerobic rice production could serve as a guide for decision- and policy-makers when developing long-term programs and plans for climate change adaptation and mitigation.

2.7.5. Crop simulation models used for climatic change effects in rice crop

Saseedran et al. (2000) calibrated and validated the CERES-Rice v3 model which accurately predicts rice production in Kerala State, India's tropical and humid environment. When examining how climate change is affecting the state's rice productivity, the Jaya variety is employed. The findings of this study showed that, under the anticipated climate change scenario used for the study, an increase in rice yields (under rainfed circumstances) is possible in the state of Kerala by the middle of the next century. Additionally, due to the increase in temperature brought on by the buildup of greenhouse gases in the atmosphere, crop duration was seen to be decreasing in every region in the state. The best times to transplant rice were determined using the probability of rainfall events calculated using ClimProb, and using the target yields predicted by the CERES-Rice v3.0 (Saseendran et al., 1998). The best times to transplant under rainfed conditions were between the 23rd and 26th week for more than one rice cropping system per year and between the 26th and 32nd week for a rainfed monocrop.

Basak et al. (2010) evaluated the impact of climate change on the production of two kinds of Boro rice using the DSSAT model. For 12 locations (districts) in Bangladesh, the yield of the Boro rice varieties BR3 and BR14 have been simulated for the years 2008, 2030, 2050, and 2070. Due to climate change, the model projected considerable yield losses for both kinds of boro rice; for both rice varieties, average yield reductions of over 20 % and 50 % were expected for the years 2050 and 2070, respectively. Increases in solar

radiation and CO_2 concentration have been found to improve rice yield to some amount, but their impact is not as great as that of temperature, which reduces yield when daily temperatures rise. It has also been discovered that variations in rainfall patterns during the growing season have an impact on rice output and water requirements. It has been discovered that rising temperatures and sun radiation shorten the time that rice varieties spend in physiological maturity. Additionally, model findings imply that climatic change may make rice production more susceptible to transplanting date. The DSSAT modelling method might be helpful for analyzing the effects of management techniques and climate change on various rice types and other crops.

Oteng-Darko (2012) simulated the yield of rice under various climate change scenarios in Ghana by using the CERES-rice model which was calibrated and evaluated. Weather data of eighteen years was used to run the model. He concluded that the model was sensitive to various weather parameters like temperature, rainfall, solar radiation and CO_2 concentration and these have an effect on rice yield. An increase or decrease of temperature by 4 °C caused a reduction in yield by 34 % when compared to the base scenario of 2006. The CERES-Rice model in the DSSAT was used to study the impact of climate change on rice and for further development of adaptation policies to maintain rice production over the western zone of Tamil Nadu. From the study, it was shown that rice yield was expected to decrease by 4 to 56 % with an increase in temperature by 1 to 5 °C from normal during various dates of planting *i.e.* June 1st to July 15th (Bhuvaneswari et al., 2014).

In order to comprehend the impact of climatic variability on rice-wheat productivity over 5 selected areas during the previous 25–30 years and the fluctuation observed in the Indo-Gangetic Plains, Subash & Mohan (2012) simulated rice-wheat system yield using DSSAT-CSMv4.5. Except for Hisar, none of the sites experienced a major shift in rainfall throughout the growth seasons for either wheat or rice. Based on a comparison of observed and simulated rice and wheat production, it can be seen that there is a high degree of agreement between them. This is significant at the P 0.05 level for all sites except Samastipur. Mishra (2013) studied the spatial variability of rice and wheat yield in the Indian Ganga Basin using DSSAT. The studies found that under projected climate (using regional climate models) showed a decrease in the yield of rice and wheat in the upper and middle Indian Ganga Basin during the 2011-40 periods.

The productivity trends in rice due to climatic variability were simulated by Bemal et al. (2013) using DSSAT for the eastern agroclimatic zone of Haryana during the period of 1978- 2008 and compared this with the on-farm productivity. According to the results, increasing the minimum temperature by 0.5 °C from the average (1977–2008) would have a detrimental influence on simulated rice output, however increasing the maximum temperature by up to 1 °C would allow for increased yield.

Nyang'Au et al. (2014) validated the DSSAT- Ceres model for rice growth during the 2011 cropping season for IR 2793-80-1 and Basmati 370 cultivars under the System of Rice Intensification in Mwea and Western Kenya, determined the Genetic coefficients for rice crop and conducted sensitive analysis for irrigation schemes. According to the study, increasing both maximum temperature and minimum temperatures has an impact on grain yield. Increased atmospheric CO_2 concentration and solar radiation resulted in increased grain yield under SRI and concluded that the Kenyan weather affects rice productivity under SRI .

Dias, (2016) used a validated DSSAT model to forecast the rice yield for the *Yala* season in the mid-centuries and a decreasing trend of yield was observed along with a reduced growth period. The effect of altering the planting window on rice production was simulated by Azdawiyah et al. (2016) using DSSAT under different climate conditions up to 2080 year. The meteorological data was generated from PRECIS by Malaysian Meteorological Services. To analyze the effects of weather trends on yield, the calibrated model predicted the yield output under the expected weather circumstances. The results showed that seasonal total rainfall and daily sun radiation averages have the biggest effects on annual crop production. The findings indicate that altering the planting date enhanced rice production during the major season, however shifting the planting date lowered rice production during the off-season.

Ray, (2018) studied the effect of changing climate on the yield of the *Swarna* rice variety through sensitivity analysis in the CERES rice model in the Keonjhar district of Odisha and it was found that an increase in both maximum temperature and minimum temperature has a negative impact on the yield of rice. Kant et al. (2018) experimented with three rice varieties CAU-R1, Shahsarang-1 and Lumpnah-1 at Umiam, Meghalaya and concluded that the DSSAT- CERES rice model can be used for predicting the yield of the varieties considered under the study, even then calibration may be done for close

prediction of yield and phenophases. It was found that the model successfully predicted yield at different levels of nitrogen. Chaudhari et al. (2019) studied in the south Gujarat region where they evaluated the impact of temperature and CO_2 on rice growth and yield using DSSAT. He observed that a rise in temperature by 1-2 °C leads to a reduction in yield by 3.25 % to -9.47 % while a decrease in temperature by 1 to 2 °C leads to an increase in yield by 5.93 %. Islam, (2021) conducted an experiment to study the DSSAT-CERES rice model simulation of upland rice yield under different temperatures. Results showed that a moderate temperature of 28 °C gave the highest simulated yield while a maximum temperature of 32 °C gave the least simulated yield.

2.7.6. Crop Simulation Model Limitations

Despite the advancement of a few irrigation technologies, both GIS-based and without integration with GIS, remote sensing, and yield mapping, are not popular among farmers and irrigation specialists due to the complexity involved in numerous parameters and temporal data. Running point-based crop models at limited range within a field is one way to get around spatial resolution, as is using geospatial technologies to apply models to regions with similar plant responses. Analyzing the geographical and temporal patterns of vegetation indices with the help of Unmanned Aerial Vehicles (UAVs) enables the collection of timely information on soil and crop variability (Ehmke, 2013; Lu et al., 2022a). With this data with yield mapping analyses, crop models may be built to identify regions of the field that are stable through time and space. As a result, new sensors, communication technologies, and algorithms for providing geographical inputs for precision farming, as well as statistical and model-based analyses, are assisting in overcoming the barrier of spatially variable data availability. Furthermore, most models are unable to predict changes in climate variability on a local scale, as well as the frequency of extreme occurrences such as storms and droughts. Despite the fact that changes in climatic variability, such as increases in the frequency of drought and storms, could have a large impact on crop yields, GCMs have yet to be able to make trustworthy projections (Oteng-Darko et al., 2013; Corbeels et al., 2018). Because crop models are not universal, the user must select the best-suited model for his experimental purpose. As a result, estimates are used to analyses the potential implications of climate change. Furthermore, most models are unable to predict changes in climate variability on a local scale, as well as the frequency of extreme occurrences such as storms and droughts. Furthermore, agricultural models reflect systems for which some components' behavior is not fully

known or regulated, and differences between model output and real-world systems cannot be completely explained (O. Rauff & Bello, 2015) . Crop models, as a result of a lack of understanding of natural processes and computer power limitations, are unable to provide reliable estimates. Another limitation of these models is that they do not simulate on real-time basis, and some are not user-friendly.

The model validation process is difficult since it requires testing multiple hypotheses at the same time. Field data is frequently insufficient for conclusive validation because characteristics and driving factors are derived from site-specific conditions. Soil heterogeneity and variances in measured metrics are caused by husbandry practices and soil properties. Crop data captures soil heterogeneity and seasonal environmental factors. The model's success is determined by the quality of its input data, which frequently includes enormous volumes of data on above-ground crop growth and development. Accurate meteorological data is necessary for simulation models, and sampling errors can cause data inconsistencies. The ideal crop model would physically and biologically explain correlations between variables and universally applicable real-world behavior, but this is difficult due to the complexity of biological systems and unknown activities. Obtaining precise system characteristics and input data for the crop environment is a major job (Jame & Cutforth, 1996; O. Rauff & Bello, 2015).

Statistical, Mechanistic, Deterministic, Stochastic, Dynamic, Static, and Simulation models are used to evaluate and predict crop growth and production. Crop growth models are an effective tool for predicting how climate change would affect crop yield and growth. These models can be used for a wide range of agricultural problems. Human resource competence must be strengthened, and proven simulation models must be built all around the world. Model development and deployment as a research tool can aid in the discovery of knowledge gaps, allowing for more efficient and targeted study design. Models based on adequate physiological data can be extrapolated to alternate cropping cycles and locales, allowing for the assessment of temporal and geographical variability. The effectiveness of most models is unknown because they are either untested or undertested. It is true that developing models is simpler than testing them. Many agronomists are baffled by the situation. They are discouraged by the complexity of the models, the absence of model testing, and the unavoidable errors that arise during such testing. Hence, crop models' efficacy in agronomy has been significantly questioned.

Unfortunately, some of the misunderstanding arises from people who believe that crop modelling will solve all of agriculture's problems and that crop models can be applied to every environment. More training is needed because most agronomists are unfamiliar with crop growth modelling and systems-approach research. A model that has been thoroughly calibrated and tested can be used to conduct research that saves time and money while simultaneously making a significant contribution to the creation of sustainable agriculture that fulfils the world's food demands.

2.8. Post-harvest rice field management: special emphasis on GHGs emissions

According to Smith et al. (2014), the production of rice accounts for between 9 and 11 % of greenhouse gas emissions in the agricultural sector globally. According to Sistani et al. (2011), Linquist et al. (2012), and Carlson et al. (2016), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the main greenhouse gases (GHGs) released. In rice farming, methane emissions are very important. As a result of their 28 and 265 times greater warming potentials than CO_2 (Smith et al., 2014; Belenguer-Manzanedo et al., 2022), methane and N_2O have a greater effect on global warming. According to Naser et al. (2019), CH_4 may predominate the crop's net greenhouse gas content, especially in rice paddies. One of the primary drivers of CH_4 production is flooding circumstances during rice farming (Neue et al., 1996).

Temperature and moisture have important roles in regulating soil organic matter and rice straw decomposition, which contributes to GHG emissions. Increases in temperature are associated with increased OM decomposition and carbon emissions (Huang et al., 2015; Tang et al., 2016; Zhang et al., 2020b). Soil moisture determines oxygen diffusion and substrate mobility (Agehara & Warncke, 2005). In flooded soils, anaerobic conditions promote lower mineralization rates (Li et al., 2021). Studies on the interaction effect of moisture and temperature on rice straw breakdown and organic matter mineralization have been undertaken, but the majority are under controlled conditions (Devêvre & Horwáth, 2000; Benbi & Khosa, 2014; Lu et al., 2021).

Gummert et al. (2020) evaluated how mechanized post-harvest processes affected energy efficiency, income, and greenhouse gas emissions in small rice farms in Myanmar's Ayeyarwaddy delta. Results reveal that mechanical procedures boost net revenue by 30-50 % over traditional practices, reduce post-harvest losses, and improve rice quality. The study also highlights the importance of combined harvesting and flatbed dryer and

hermetic storage in post-harvest management, providing valuable information for policymakers in South and Southeast Asia.

Martínez-Eixarch et al. (2021) studied the Mediterranean rice agrosystem (Ebre Delta, Catalonia) aimed to improve the accuracy of the CH_4 budget in paddy rice fields. The study evaluated the cumulative and temporal pattern of CH_4 emissions and conducted multi-variate analyses. Results showed that the fallow season, which is often neglected, is the most significant source of CH_4 emissions. The main regulating factors in the growing season were positively associated to water level and plant cover, while soil redox was adversely related. The study emphasizes the importance of measurement programs covering the entire crop field cycle for effective mitigation strategies based on straw and water management.

Belenguer-Manzanedo et al. (2022) evaluated the impact of flooding and straw incorporation timing on greenhouse gas exchanges in the post-harvest of paddy rice cultivation in the Ebro delta area of Spain. A field experiment showed that non-winter flooding and late straw incorporation strategies reduced greenhouse gas emissions by 206% compared to conventional post-harvest management. Avoiding winter flooding reduced CH_4 emissions significantly, while delay straw incorporation prevented CH_4 and CO_2 emissions. The study concluded that post-harvest management affects net global warming potential without compromising sequestration budget.

2.9. Rice yield prediction in relation with changing climate scenarios

To observe traditional rice cultivation practices and collect data on crop yields, input use, and labour requirements. The paper presents the results of the study, including the benefits and challenges of traditional rice cultivation in Kerala. The authors highlight the importance of traditional rice cultivation practices for maintaining the ecological balance of the region, preserving traditional knowledge and cultural heritage, and providing sustainable livelihoods for farmers. The authors also discuss the challenges faced by traditional farmers in the region, including the lack of government support and incentives for traditional farming practices, the availability and affordability of inputs, and the competition from commercial rice production. Overall, the study provides a valuable contribution to the understanding of traditional rice cultivation practices in Kerala and the importance of maintaining these practices for the sustainability of the environment and the livelihoods of farmers in the region. The study highlights the need for greater support and

recognition of traditional farming practices and the integration of traditional knowledge and modern science in sustainable agricultural development.

Roy & Saha (2018) aimed to assess the land suitability for paddy cultivation in the Hinglo River basin of eastern India using the Analytic Hierarchy Process (AHP). The authors collected data on various physical, chemical, and biological parameters of soil and water, as well as climatic conditions, and then used AHP to prioritize and weight the criteria based on their relative importance. The authors identified four different land suitability classes, ranging from highly suitable to not suitable, based on the final AHP scores. The results of the study can be useful for decision-makers and farmers to identify the most suitable areas for paddy cultivation in the Hinglo River basin, and to plan appropriate land use practices to maximize the yield and minimize the environmental impact. Overall, the study demonstrated the effectiveness of using AHP for land suitability assessment, especially in areas where the availability of data is limited.

Saaty et al. (2001) study the basic concepts and principles of the AHP, such as the fundamental scale of measurement, pairwise comparisons, and the use of matrices to represent decision problems. Saaty then discusses the four main steps in the AHP process: modelling the decision problem, structuring the decision hierarchy, making pairwise comparisons, and synthesizing the results. The study also presents several applications of the AHP in different fields, such as engineering, business, and social sciences. Saaty emphasizes the flexibility and versatility of the AHP and how it can be adapted to different decision problems and contexts.

Duc (2006) investigated the use of GIS and the Analytic Hierarchy Process (AHP) for land-use suitability analysis in Vietnam. The study aimed to identify the most suitable land use types for an area in central Vietnam based on various criteria, such as slope, soil type, and land cover. The study used a combination of AHP and GIS to generate a suitability index for each land use type. The AHP was used to determine the relative importance of each criterion and to assign weights to each criterion based on their relative importance. The GIS was used to analyse the spatial distribution of each criterion and to create a suitability map for each land use type. The results showed that the most suitable land use type for the study area was agroforestry, followed by fruit orchards and vegetable gardens. The study also found that slope and soil type were the most important criteria in determining land use suitability in the study area. Overall, the study demonstrates the

effectiveness of using GIS and AHP for land-use suitability analysis, which can help decision-makers in identifying the most appropriate land-use types for a given area based on a set of criteria.

Al-Hanbali et al. (2021) conducted a study on land suitability analysis for paddy fields in Tanzania using a GIS-based analytical hierarchy process. The research aimed to identify the potential areas for rice cultivation by integrating various factors such as climate, soil, topography, and land use. The study used a multi-criteria decision analysis approach to determine the weightage of each factor and to create a suitability map for rice cultivation. The results showed that 32 % of the total area was highly suitable for rice cultivation, while 44 % of the area was moderately suitable. The study also identified some areas that were unsuitable due to environmental constraints. The research findings provide valuable insights for policymakers and agricultural planners to improve rice production in Tanzania by targeting suitable areas for cultivation. The use of a GIS-based analytical hierarchy process can also be applied to other regions to assess land suitability for other crops.

Robertson & Oinam (2023) aimed to develop a rice suitability map in a river catchment using the Analytic Hierarchy Process (AHP) approach. They collected data on various criteria such as topography, soil, climate, and water availability, and used AHP to weigh and rank these criteria based on their importance for rice cultivation. The authors then combined the rankings to generate a rice suitability map for the study area. The results showed that soil was the most important criterion for rice cultivation, followed by water availability, climate, and topography. The suitability map generated using AHP showed that the majority of the study area was highly suitable for rice cultivation, with some areas having moderate or low suitability. The authors suggest that this approach could be useful for land-use planning and decision-making related to rice cultivation. Overall, the study provides a useful example of how AHP can be applied to assess land suitability for specific crops and highlights the importance of considering multiple criteria when making land-use decisions.

Orhan et al. (2021) aimed to assess the site suitability and map the areas suitable for rice cultivation in the delta plain of Turkey using multi-criteria decision analysis based on fuzzy analytic hierarchy process (FAHP) and technique for order of preference by resemblance to ideal solution under semi-humid ecological conditions. The study

considered several criteria, including soil, climate, topography, hydrology, and land use, and assigned weights to each criterion based on the FAHP. The TOPSIS method was used to rank the sites based on their suitability for rice cultivation. The study found that the highest-ranked sites were located in the western and northern parts of the study area, while the lowest-ranked sites were located in the south and east. The results showed that the proposed MCDA approach using FAHP and TOPSIS can effectively assess the suitability of different sites for rice cultivation, which can be useful for decision-making in agricultural planning and land-use management.

Chandrakala et al. (2019) present a land suitability evaluation study for major crops in the tropical humid region of Kerala, India. The study aimed to identify the most suitable land for each crop and provide guidance for farmers in crop selection and management. The paper begins by discussing the importance of land suitability evaluation in crop planning and management. The authors then describe the study area and the data sources used, including soil, topography, and climate data. The authors explain the methodology used for land suitability evaluation, which involved the integration of various data sources in a GIS platform. The authors used fuzzy logic-based analytical hierarchy process (AHP) to develop a land suitability index for each crop based on multiple criteria, including soil properties, topography, and climate. The paper presents the results of the land suitability evaluation for major crops in the study area, including paddy, coconut, banana, rubber, and black pepper. The authors identified the most suitable land for each crop and provided guidance for farmers in crop selection and management. The authors also discussed the limitations and implications of the study. The authors noted that the study was limited by the availability and quality of data, and the need for more detailed data in certain areas. However, the study provides valuable guidance for farmers and policymakers in crop planning and management, which can help improve agricultural practices and increase crop yields in the region.

Shanmugapriya et al. (2019) provides an overview of the use of remote sensing in agriculture. The authors reviewed various studies that have applied remote sensing techniques for monitoring crop growth, yield prediction, crop mapping, and detection of crop stress. The paper begins by discussing the importance of agriculture and the need for improved agricultural practices to meet the growing demand for food. The authors then describe the basic principles of remote sensing and the types of sensors used for agricultural applications, including optical, thermal, and radar sensors. The authors review

several studies that have used remote sensing for crop monitoring and yield prediction. They discuss the use of vegetation indices to monitor crop growth and detect stress. The authors also describe the use of thermal sensors to detect water stress in crops. The paper also discusses the use of remote sensing for crop mapping and classification. The authors review studies that have used optical and radar sensors to map crops and estimate crop acreage. They also discuss the use of hyperspectral sensors for crop classification. Finally, the paper discusses the potential of remote sensing for precision agriculture. The authors describe how remote sensing can be used to guide site-specific management practices, such as variable rate application of inputs. They also discuss the use of unmanned aerial vehicles (UAVs) for high-resolution remote sensing.

Ajith et al. (2017) aimed to estimate rice acreage in Thanjavur, Tamil Nadu, India, using Landsat 8 OLI images and GIS techniques. The authors used supervised classification to extract rice paddies from the images and then calculated the rice acreage using the classified image and ground truth data. The accuracy assessment showed an overall accuracy of 89.6 % and a kappa coefficient of 0.88, indicating good classification performance. The authors concluded that the use of remote sensing and GIS techniques can provide accurate and timely information on rice acreage for efficient planning and management of agricultural activities. Overall, the study provides valuable insights into the application of remote sensing and GIS in rice acreage estimation.

Ayehu et al. (2019) explore the use of Geographic Information Systems (GIS) and multi-criteria decision analysis (MCDA) techniques for assessing land suitability for rice production in Ethiopia. The study involves the use of various criteria, such as soil properties, climate, and topography, and a weighted overlay analysis to generate suitability maps for rice cultivation. The results indicate that about 23 % of the study area is highly suitable for rice cultivation, while 40 % is moderately suitable. The study also highlights the importance of considering both physical and socio-economic factors in land suitability assessments. Overall, the study demonstrates the potential of using GIS and MCDA techniques for effective land suitability analysis for agricultural land use planning.

Kasampalis et al. (2018) conducted a comprehensive review of the contribution of remote sensing to crop models. The study aimed to evaluate the state-of-the-art research on the integration of remote sensing data with crop models for improved agricultural management practices. The authors analysed various types of remote sensing data, such as

optical, thermal, and radar data, and their application in crop models. The study also reviewed different crop models, including statistical, process-based, and machine-learning models, and their integration with remote sensing data. The authors highlighted the benefits of using remote sensing data in crop models, such as providing a large-scale and synoptic view of crop conditions, improving the accuracy and efficiency of crop modelling, and enabling the monitoring of crop growth and yield. The study also identified several challenges in integrating remote sensing data with crop models, such as the complexity of the models, the need for accurate calibration and validation, and the availability and quality of remote sensing data. Overall, the study demonstrated the significant potential of integrating remote sensing data with crop models to enhance crop productivity and food security. The authors also suggested future research directions, such as the integration of multiple sources of remote sensing data and the development of more accurate and efficient crop models.

Myneni & Williams (1994) investigated the relationship between the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) and the Normalized Difference Vegetation Index (NDVI). The authors used data from the Advanced Very High-Resolution Radiometer (AVHRR) to study the relationship between FAPAR and NDVI in several ecosystems. They found that FAPAR and NDVI are highly correlated in most vegetation types, but the relationship between the two indices is affected by the presence of non-photosynthetic vegetation, such as bare soil or snow. The authors concluded that FAPAR and NDVI can be used as complementary measures of vegetation activity, with FAPAR providing a more accurate estimate of photosynthetic activity and NDVI providing a more sensitive measure of vegetation greenness. The study provides important insights into the use of remote sensing data for monitoring vegetation dynamics and ecosystem processes.

Pazhanivelan et al. (2022) attempted to predict spatial rice yield using multiple linear regression analysis, a semi-physical technique, and assimilating SAR satellite-derived data with the DSSAT crop simulation model. The study utilized SAR data, land surface temperature, rainfall, and crop phenological data to estimate the rice yield. The results of the study showed that the semi-physical approach using SAR and land surface temperature as inputs provided the highest accuracy in estimating rice yield. The study also showed that the assimilation of SAR data into the DSSAT model improved the accuracy of the model in predicting rice yield. Overall, the study demonstrates the potential

of using SAR data in combination with crop models to accurately estimate rice yield in spatially explicit locations.

Chaurasiya et al. (2017) proposed a semi-physical approach for sugarcane yield modelling using remotely sensed inputs. The study was conducted in the sugarcane-growing region of Maharashtra, India. The proposed approach combined spectral vegetation indices, meteorological data, and a sugarcane growth model to estimate sugarcane yield. The study found that the proposed approach could accurately estimate the sugarcane yield with an R^2 value of 0.88. The authors concluded that the semi-physical approach can be used as an effective tool for sugarcane yield estimation and monitoring. The study highlights the potential of using remote sensing and sugarcane growth models for yield forecasting and management in sugarcane cultivation.

Rugira et al. (2020) used the Decision Support System for Agrotechnology Transfer (DSSAT) CERES-Maize model to identify the best irrigation management and date of sowing for improving maize yield in northern China. The study involved field experiments conducted over two growing seasons with six treatments of different sowing dates and irrigation regimes. The results showed that the best sowing dates were from April 25 to May 5 and that the optimum irrigation regime was 75 % of field capacity during the vegetative stage and 70 % during the reproductive stage. The study also found that using this optimal combination could increase maize yield by up to 16.5 %. Overall, the study demonstrates the potential of using DSSAT CERES-Maize to identify optimal management strategies for improving maize yield in different regions. Ahmad et al. (2018) developed a method for forecasting spring maize yield in Faisalabad, Punjab, Pakistan, using remote sensing and crop modelling. The model yield prediction results were more accurate than remote sensing, with an RMSE of 255 kg ha^{-1}.

Scaria & Vijayan (2015) present a study of the spatio-temporal changes in the cropping pattern of paddy fields in Kerala state, India, with a focus on the Palakkad district. The study aimed to identify the patterns of change in the cropping intensity and diversification in the paddy fields and the factors influencing these changes. The study begins by providing an overview of the agricultural practices in Kerala and the importance of paddy cultivation in the state's economy. The authors then describe the study area and the data sources used, including satellite images, topographic maps, and field surveys.

The authors explain the methodology used for the study, which involved the use of remote sensing and GIS techniques to analyse the spatio-temporal changes in the cropping pattern of paddy fields in the Palakkad district. The authors also conducted field surveys to validate the results of the remote sensing analysis and identify the factors influencing the changes in the cropping pattern. The paper presents the results of the study, including the changes in the cropping intensity and diversification in the paddy fields in the Palakkad district between 1973 and 2011. The authors identified a significant decline in the cropping intensity and a shift towards diversification in the paddy fields during this period. The authors also identified the factors influencing these changes, including the availability and affordability of labour, the profitability of different crops, and the changes in land use policies and regulations. The authors discuss the implications of the study for sustainable agricultural development in the region, including the need for policies and interventions to promote the sustainability of paddy cultivation and maintain the ecological balance of the region. The study demonstrates the potential of remote sensing and GIS techniques for analysing and monitoring changes in agricultural practices and provides valuable insights for policymakers and researchers in sustainable agricultural development.

Raju et al. (2022) focuses on the use of Sentinel-2 data and GIS techniques for mapping rice areas in the Palakkad district of Kerala, India. The study aimed to provide accurate and timely information on rice areas for efficient crop management and decision-making. The paper begins by discussing the importance of rice cultivation in Kerala and the need for accurate and up-to-date information on rice areas. The author then describes the study area and the data sources used, including Sentinel-2 satellite imagery and field data collected from the district agriculture office. The author explains the methodology used for rice area mapping, which involved preprocessing of the Sentinel-2 data, including atmospheric correction, radiometric correction, and cloud masking. The author then used supervised classification techniques in GIS to map rice areas in the study area. The paper presents the results of the study, including the accuracy assessment of the rice area map. The author reports an overall accuracy of 92 % and a kappa coefficient of 0.88, indicating a high level of agreement between the classified map and the ground truth data. The author also discusses the implications of the study for rice crop management and decision-making. The accurate and up-to-date information on rice areas provided by the study can help farmers and policymakers make informed decisions on crop management, irrigation, and fertilizer application. Overall, the paper provides a valuable contribution to the use of

remote sensing and GIS techniques for rice area mapping in Kerala. The study demonstrates the potential of Sentinel-2 data and GIS techniques for accurate and timely crop mapping, which can help improve agricultural practices and decision-making in the region.

Saseendran et al. (2000) conducted a study on the effects of climate change on rice production in Kerala, India. The authors used simulation models to predict the impacts of climate change scenarios on rice production in the region. The study focused on two major rice-growing districts of Kerala and considered two climate change scenarios (A1B and A2) for the period from 2010 to 2099. The authors found that both scenarios resulted in an increase in temperature and a decrease in rainfall, which negatively affected rice production. The study also predicted a decline in rice yield by up to 16 % under the A2 scenario and up to 10 % under the A1B scenario. The authors highlighted the importance of developing adequate adaptation methods to reduce the negative effects of climate change on rice production in the region. The study emphasizes the need to recognize the possible effects of climate change on agriculture, as well as the need for suitable actions to meet the difficulties that climate change presents.

Nguyen (2016) reviews the impacts of climate change on rice production and food security, with a focus on Southeast Asia. The paper begins by providing an overview of the importance of rice as a staple food in the region, and then discusses the various ways in which climate change is expected to affect rice production, including changes in temperature, rainfall patterns, and extreme weather events. The paper then goes on to review a range of studies that have attempted to model the impacts of climate change on rice production, including studies that use CSMs and remote sensing data. The author notes that while these studies have identified a range of potential impacts, there is still considerable uncertainty regarding the magnitude and timing of these impacts. The paper also discusses some of the potential adaptation measures that could be implemented to help mitigate the impacts of climate change on rice production and food security, including improved water management, crop breeding programs, and the development of new cropping systems. Overall, the paper provides a useful overview of the potential impacts of climate change on rice production and food security in Southeast Asia and highlights the importance of developing effective adaptation measures to help farmers and communities cope with these impacts.

The comprehensive literature analysis concludes by highlighting the critical importance of rice agriculture on an international, Indian, and regional scale—with a particular emphasis on the Keralan context. The adoption of innovative water and nutrient management practices, coupled with the integration of cutting-edge Crop Simulation Models (CSM), emerges as a promising avenue for optimizing cultivation strategies. The incorporation of CSMs not only facilitates enhanced prediction of rice yields in future scenarios but also aids in the development of sustainable and efficient management practices. Moreover, the review highlights the demanding need for suitability mapping and robust post-harvest management strategies in paddy fields to minimize losses and ensure food security. In core, the synthesis of literature emphasises the multifaceted dimensions of rice cultivation, calling for a holistic approach that combines technological advancements, predictive modelling, and sustainable practices to ensure the resilience and productivity of rice ecosystems at local and global scales.

Materials and Methods

3. Materials and Methods

Field experiments on various rice water and nutrient management strategies were conducted from 2018 to 2023 to study the **"Application of crop simulation models for water and nutrient management on growth, and productivity of rice under different climate scenarios"**. A detailed description of various materials used, experimental protocols, procedures and methodology adopted in the present study are described in this chapter. It has been planned into seven numbers of experiments.

3.1. Experiment -1

Assessing the influence of nutrient management and method of irrigation on four different rice cultivars

The first experiment was designed to evaluate the effect of different levels of nutrient management and methods of irrigation on four different rice varieties, commonly cultivated in Kerala on different rice growth parameters and the methodology for this experiment is being detailed hereunder.

3.1.1. Design and Layout

In general, rice grows during three distinct seasons: *Viruppu*, *Mundakan*, and *Puncha*. The first agricultural season, *Viruppu* or autumn spans from April - May to September - October. *Mundakan* or winter is the second harvest, lasting from September - October to December - January. *Puncha* is the third crop, which starts in December-January and lasts till March-April. The experimental design was a randomized block design conducted during the *Mundakan* season of 2018 (September 2018- January 2019) with four different rice varieties, viz., *Jyothi* (V1)*, Jaya* (V2)*, Kanchana* (V3)*, and Uma* (V4) in the lysimeter boxes of the Land of Water Management Research Group at Centre for Water Resources Development and Management (CWRDM), Kunnamangalam, Kozhikode, Kerala, India. Paddy seeds were procured from the Regional Agriculture Research Station in Pattambi, Kerala. Each experimental subplot was a 6 m^2 rectangle box with 2 m width and 3 m length. The treatments that were attempted are given the Table 3.1. Treatments consist of (1) method of irrigation, which consists of (a) water-logged/ flooded (I1) and (b) alternate wetting and drying (AWD) (I2); and (2) nutrient management practice treatment, which consists of applying (a) Absolute control (No NPK application) (N1), (b) 100 % recommended dose of NPK (N2), and (c) 120 % recommended dose of N

and 100% P & K application (N3). The recommended dose of fertilizers (NPK) was applied as per the package of practice of Kerala Agricultural University (KAU 2016) to each treatment.

Table 3.1. Experiment 1- treatment details

Treatments	
Irrigation	**Nutrient levels**
I1- Water logged/ flooded	N1- Absolute control (No NPK application)
I2- Alternate Wetting and Drying (AWD)	N2- 100 % Recommended dose of NPK application N3- 120% Recommended dose of N and 100% P&K application

All the cultural and crop management practices were adopted as per the package of practices of Kerala Agricultural University (KAU, 2016). Initially Land preparation was carried out as per the standard procedure (Fig.3.1) and transplantation of 25-day-old seedlings (Fig.3.2) were conducted per the recommendations of package of practices of the Kerala Agricultural University (KAU, 2016). carried out according to the treatments. The experiment comprised twenty-four treatments with three replications and was conducted in puddled soil (Fig.3.3 & Fig.3.4).

Fig.3.1. Preparation of experimental plot-Initial stage

Fig.3.2. Transplantation of seedlings to experimental plots

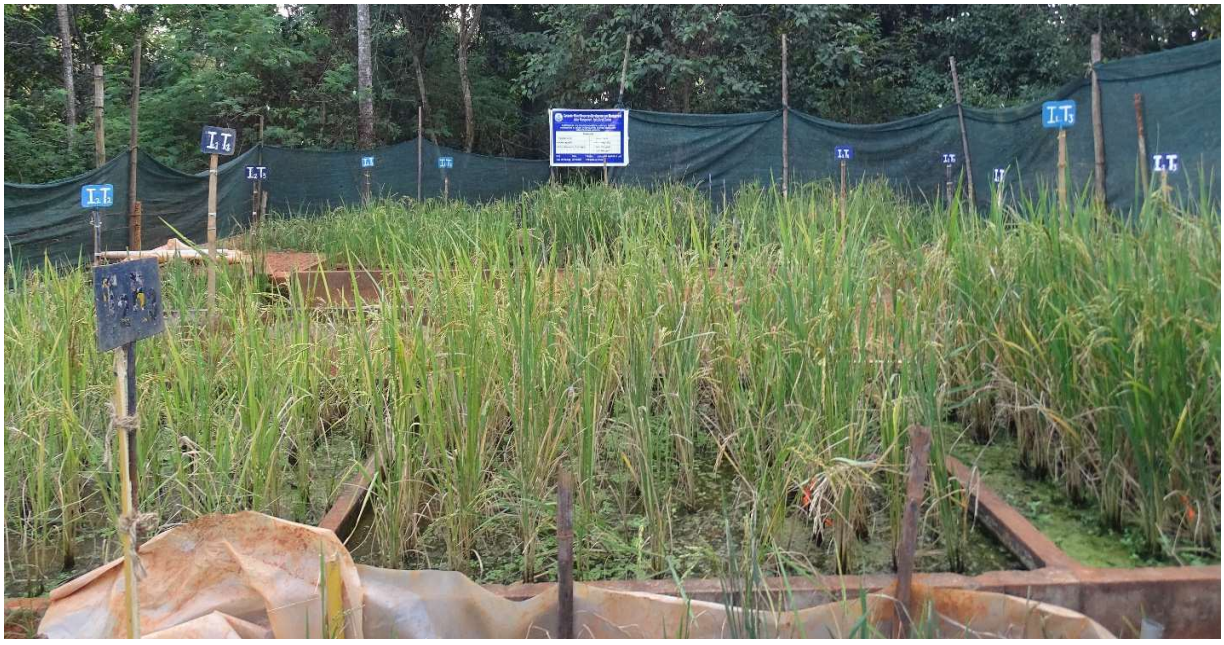


Fig.3.3. Experimental field for assessing the influence of nutrient management and method of irrigation on four different rice cultivars

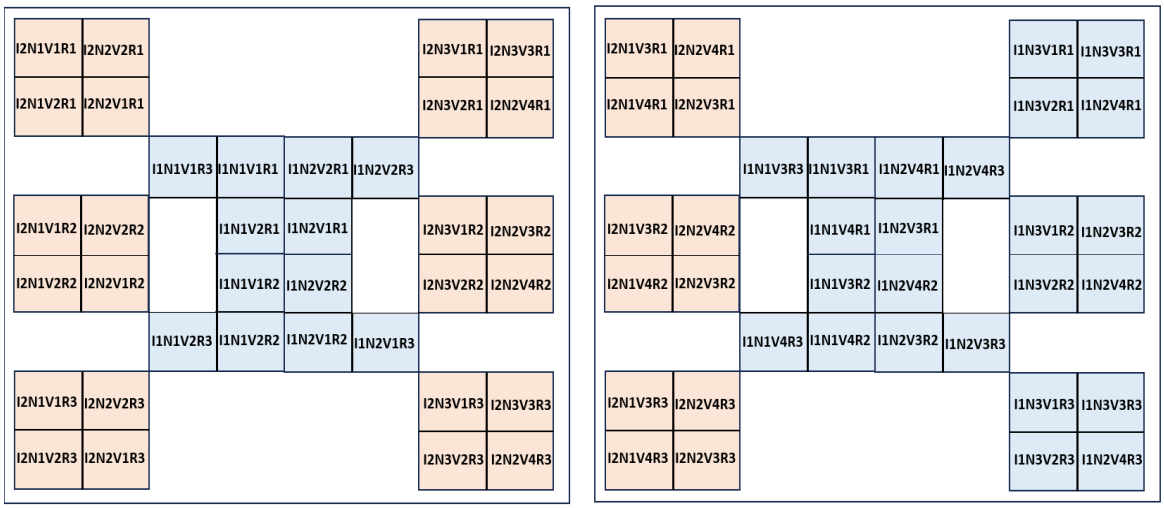


Fig.3.4. Experiment 1- diagrammatic representation of experimental field (I1- water logged/ flooded irrigation, I2- alternate wetting and drying (AWD) irrigation, N1- 0 % application of the recommended dose of nutrients, N2- 100 % application of the recommended dose of nutrients through inorganic fertilizers, N3- 120 % of the recommended dose of nutrients through inorganic fertilizers, (V1- *Jyothi*, V2- *Jaya*, V3- *Kanchana* and V4- *Uma*)

3.1.2. Description of the varieties used

Jyothi, *Jaya*, *Kanchana* and *Uma* were the four varieties used in this field experiments (Fig. 3.5 & Table 3.2).

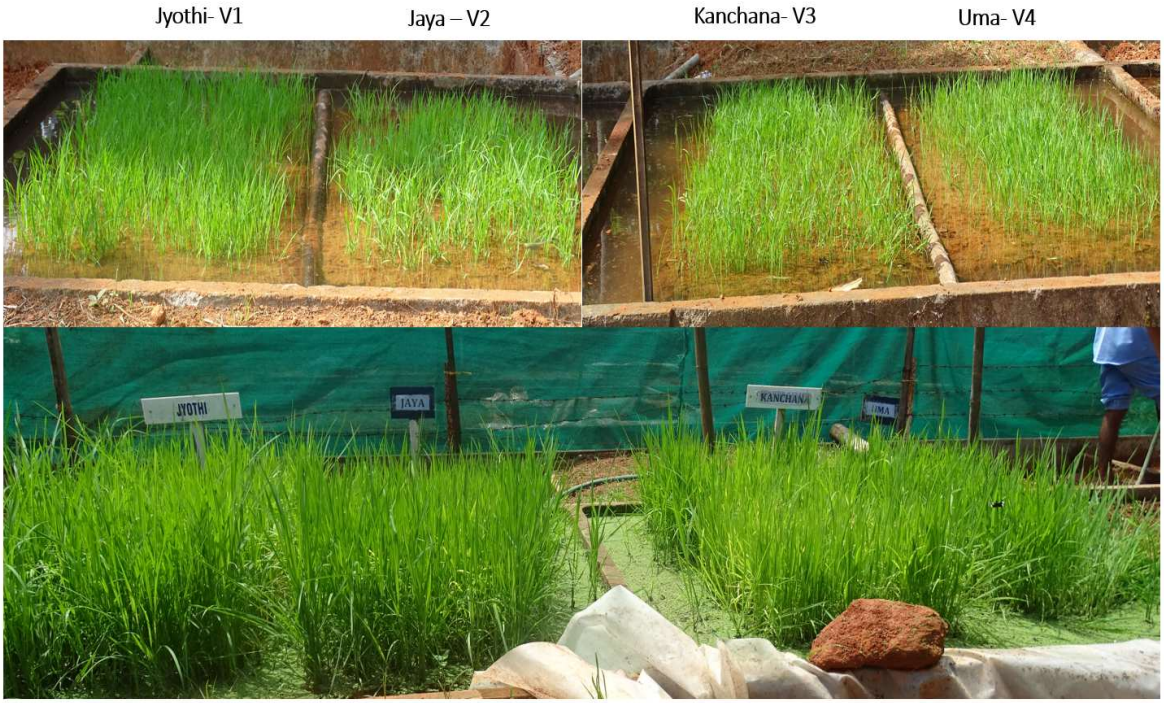


Fig.3.5. Nursery of four different rice varieties used in this experiment (V1-*Jyothi*, V2- *Jaya*, V3- *Kanchana* and V4- *Uma*)

Table 3.2. Characteristics of rice varieties used for experiments

Variety	Duration (Days)	Bran colour, grain type	Characteristics
Jyothi (PTB 39)	Short duration (110-115)	Red, Long & bold	Moderately tolerant to brown plant hopper and blast, vulnerable to sheath blight Appropriate for transplanting, direct seeding and special systems of Kole and Kuttanad
Jaya	Medium duration (120-125)	White, long & bold	High yield potential, very vulnerable to brown plant hopper and other pests
Kanchana (PTB 50)	Medium duration (105-110)	Red, Long & bold	Suitable for Kole and Kuttanad areas. Resistant to blast, blight stem borer and gall midge.
Uma (MO 16)	Medium duration (120-135)	Red, Medium & bold	Non lodging, resilient to gall midge and brown plant hopper, bold Biotype-5. Dormancy up to 21 days.

(Source: KAU, 2016)

Jaya is a medium-duration variety, which has a growth period of 120-125 days Jaya has been developed from a cross between Taichung (Native) 1 and T-141 at all local photosensitive varieties of rice found in Orissa. Jaya has been grown all over India during the *kharif* and *rabi* seasons under irrigated conditions. Jaya has great production potential but is vulnerable to brown plant hopper (BPH) and other pests.

Jyothi or PTB 39 is a short-duration variety cultivated in Kerala during all the three seasons and is a short duration variety of 110-115 days growth period. Moderately

resistant to BPH and blast disease and prone to sheath blight; ideal for transplanting, direct seeding, and special systems of Kole and Kuttanad regions. It has wider adaptability. It is highly suited to wetland areas. It has been developed from the cross between PTB-10 and IR 8.

Kanchana (PTB39) is a short-duration variety which has a duration of 105- 110 days. It has been developed from the cross between Jajati and Mehsuri in 1993. These are tall in nature and resistant to blast, blight and stem borer. Appropriate for all three paddy crop seasons of Kerala

Uma (MO 16) is a semi-dwarf rice variety with medium duration. The cultivation period ranges from 115-120 days in the *Puncha* season and 120- 135 days for the *Virippu* (autumn) season. The Kerala Agricultural University developed this variety which is iron and zinc rich. The variety has Non-lodging, BPH-resistant, and GM Biotype-5. Seed dormancy might last up to three weeks. Variety is suitable for three seasons, particularly the additional *Virippu* crop season in Kuttanad. This is one of the most common rice varieties used in the State of Kerala, which currently takes up more than 60 % of the State's rice land and more than 80 % of the land in Kuttanad (Devika et al., 2006).

3.1.3. Climatic parameters

Different climatic parameters namely, minimum temperature, maximum temperature, maximum relative humidity, minimum relative humidity, rainfall, solar radiation, and pan evaporation were measured throughout the crop period from the meteorological observatory of CWRDM.

3.1.4. Soil Characters

Soil samples were randomly gathered from experimental fields, encompassing two distinct depths: 0 to 15 cm and 15 cm to 30 cm. Subsequently, these samples underwent analysis to determine their physicochemical attributes, along with the available concentrations of nitrogen (N), phosphorus (P), and potassium (K), employing the methods outlined below. The collected samples were subjected to shade-drying, followed by pulverization and sieving through a 2 mm sieve, and then analysed for selected available nutrients in the soil science laboratory of CWRDM.

Soil Physicochemical properties

3.1.4.1. Field capacity and wilting point

The soil pore size determines how much water is retained in the soil under certain pressures. A certain amount of water will drain from a saturated soil when pressure is applied, and this process will continue until the pores have a diameter equivalent to the pressure. An important aspect of the soil is its equilibrium moisture content. Field capacity and wilting point moisture, respectively, are the amounts of moisture retained at equilibrium when a saturated soil is subjected to pressures of 1/3 and 15 bar.

Field capacity refers to the soil's capacity to retain water once excess liquid has been removed and the downward movement of water has slowed. This characteristic is often quantified as a percentage of the soil's dry weight. Field capacity represents the maximum amount of water available to plants, ensuring optimal absorption of essential nutrients and moisture. To determine field capacity, a pressure plate apparatus, comprising an air compressor, pressure line, pressure chamber, and porous ceramic plate, was employed (Richards and Fireman, 1943). This apparatus applied a suction of -1/3 atmosphere to a saturated soil sample to estimate the FC. The permanent wilting point (PWP) designates the minimum soil moisture required by a plant to prevent wilting. Once a plant depletes its water supply, it reaches the permanent wilting point, typically occurring at 15 bars. Despite some residual water in the soil at this stage, the roots encounter difficulty in extracting it, leading to the plant's inability to sustain turgor pressure and subsequent wilting and this is also estimated with pressure plate apparatus.

Procedure

Initially, the rubber rings were positioned on the porous ceramic plate, with multiple ceramic plates available for different pressures. Subsequently, the porous plate containing soil and the rubber rings was placed in a plastic tray filled with distilled water, allowing it to soak overnight. Approximately 25 g of sieved soil, passed through a 2 mm standard sieve, was then carefully placed into the rubber ring, levelled to the rim with a knife, and saturated with distilled water. Following this, the porous plate containing the prepared soil was introduced into the pressure chamber and connected to the extractor's outlet tube. The air compressor was linked to a power source, and upon activating the motor, the pressure inside the chamber was raised to the required level (1/3 bar for field capacity and 15 bars for wilting point moisture). Upon reaching equilibrium, the air

compressor and pressure line were turned off. Subsequently, excess pressure was released, and the extractor was opened to remove the pressure plate. The soil samples were then transferred into an aluminium tin, and their weight was measured. The samples were placed in an oven at 60 °C for three days, after which their remaining weight was measured. The available water content was then calculated based on the initial and final weights (R, 2002).

Calculation

Field capacity

Wt. of wet soil + aluminium tin = x g

Wt. of oven dry soil + aluminium tin = y g

Wt. of empty aluminium tin = z g

$$Feild\ capasity = \frac{water\ lost\ due\ to\ oven\ drying}{weight\ of\ oven\ dry\ soil}\ x\ 100$$

$$= \frac{(x-z)-(y-z)}{(y-z)}\ x\ 100$$

Wilting point

Wt. of wet soil + aluminium tin = x g

Wt. of oven dry soil + aluminium tin = y g

Wt. of empty aluminium tin = z g

$$Wiltting\ point = \frac{water\ lost\ due\ to\ oven\ drying}{weight\ of\ oven\ dry\ soil}\ x\ 100$$

$$= \frac{(x-z)-(y-z)}{(y-z)}\ x\ 100$$

3.1.4.2. Soil pH

The soil pH was identified using a 1:2.5 ratio soil-water suspension with glass electrode (Jackson ,1973) using an EUTECH pH & electrical conductivity meter (model number PC 510; serial number: 2237098).

3.1.4.4. Soil organic carbon

Soil organic carbon was measured using the Chromic acid wet digestion method (Walkley & Black, 1934).

Principle

In the presence of concentrated H_2SO_4, chromic acid oxidizes the organic carbon present in organic materials. When potassium dichromate and H_2SO_4 mix, nascent oxygen is produced, which reacts with carbon to form CO_2. By producing heat of dilution, the H_2SO_4 makes it simple to digest organic material. Chromic acid is only used in a limited amount for oxidation. By back titrating with 0.5N ferrous sulphate or ferrous ammonium sulphate and using diphenylamine indicator, the surplus chromic acid left unused by the organic matter is identified.

$$2K_2Cr_2O_7 + 8H_2SO_4 \rightarrow 2K_2SO_4 + 2Cr_2(SO_4)_3 + 8\,H_2O + 6\,(O)$$

$$3C + (O) \rightarrow 3CO_2$$

Materials required

(i). 1N Potassium dichromate, (ii). Diphenylamine indicator, (iii). 0.5N ferrous sulphate or ferrous ammonium sulphate, (iv). Concentrated H_2SO_4, (v). Phosphoric acid (Orthophosphoric acid 85 %), (vi) Conical flask 500 ml and (vii). Burette.

Procedure

A 500 ml conical flask was loaded with 0.5 g of soil after it had been passed through a 0.2 mm sieve. then 10 ml of 1 N $K_2Cr_2O_7$ was added, and the flask was thoroughly stirred. Then, 20 ml of concentrated H_2SO_4 was added, and the mixture was gently rotated for 1 minute to ensure that the reagent had completely contacted the soil. Add 200 ml of water, 10 ml of phosphoric acid, and 1 ml of the diphenylamine indicator after 30 minutes. Then 0.5 N of ferrous ammonium sulphate was added to the solution as a titrant. As the titration progresses, the colour changes from a dark green at first to a turbid blue. The colour abruptly changed to a bright green at the endpoint. Simultaneously perform a blank titration (without soil) and noted the volume of 0.5 N ferrous ammonium sulphate consumed for the blank.

Calculation

Wt. of soil sample taken = 0.5 g

Vol. of 1N potassium dichromate ($K_2Cr_2O_7$) used = 10 ml

Vol. of 0.5 N ferrous ammonium sulphate ($(NH_4)SO_4.FeSO_4$)

used for the blank titration = X ml

Volume of 0.5N ferrous ammonium sulphate ($(NH_4)SO_4.FeSO_4$)

used for ample titration = Y ml

X ml of $FeSO_4$ reduces 10 ml 1N potassium dichromate ($K_2Cr_2O_7$)

Therefore Y ml of ferrous ammonium sulphate ($(NH_4)SO_4.FeSO_4$)

reduces = $\frac{Y}{X}$ x 10

Hence actual quantity of 1N potassium dichromate ($K_2Cr_2O_7$) used

for oxidation of organic matter = 10- (10xY/X) ml

1ml of 1N $K_2Cr_2O_7$ = 0.003 g of C

Therefore 10-(10 x Y/X) ml of 1N $K_2Cr_2O_7$ =10 – (10 x $\frac{Y}{X}$) x 0.003 g

This is present in 0.5 g of soil

Organic carbon present in 100 g of soil =10 – (10 x $\frac{Y}{X}$) x 0.003 x $\frac{100}{0.5}$

3.1.4.5. Available nitrogen

The amount of soil available nitrogen in soil sample was determined by alkaline permanganate method (Subbiah & Asija, 1956).

Principal

Alkaline permanganate is added in excess to a known weight of soil, then the mixture is distilled. The nascent oxygen generated by $KMnO_4$ in the presence of NaOH oxidizes the organic matter already present in the soil, releasing ammonia in the process. This released ammonia is taken up by a 2 % double-indicator boric acid solution, which then transforms it into ammonium borate. This ammonium borate was titrated against H_2SO_4 reference standards.

$2KMnO_4 \rightarrow 3O + K_2O + 2MnO_2$

Organic matter → release of $R.NH_2$

$R.NH_2 + H_2O \rightarrow R.OH + NH_3$

Materials required

(i) 0.32 % $KMnO_4$ solution (3.2 g of $KMnO_4$ dissolved in 1 litre distilled water), (ii) 2.5 % NaOH solution (25 g of NaOH dissolved in litre of distilled water), (iii) 2 % boric acid (20 g of boric acid dissolved in 1 litre of distilled water), (iv) N/50 H_2SO_4, (v) Double

indicator (Bromocresol green (0.5g) and methyl red (0.1g) dissolved in 100 ml of ethyl alcohol), (vi) Distillation assembly, (vii) Burette and (viii) Beaker 100 ml.

Procedure

20 g of soil was weighed and placed into a distillation flask. The soil was then moistened with 30 ml of distilled water. 100 ml of freshly made 0.32 percent $KMnO_4$ and 100 ml of 2.5 % sodium hydroxide (NaOH) were added to the soil in the distillation flask. Kept a 100 ml beaker with 20 ml of 2 % boric acid below the condenser's delivery end in the distillation set, and collected the freed ammonia in the boric acid. Distillation should continue until no ammonia is present in the discharge. After that, N/50 sulfuric acid (H_2SO_4) used to titrate the ammonia gathered in the boric acid.

Calculation

Wt. of soil sample taken	=	20 g
Vol. of N/50 H_2SO_4 consumed	=	X ml (Titre value)
1 ml of N/50 H_2SO_4	=	0.00028 g Nitrogen
X ml of N/50 H_2SO_4	=	0.00028 x X g N
Nitrogen present in kg ha^{-1}	=	$\frac{0.00028\ (X)\ 2 \times 10^6}{20}$

3.1.4.6. Available phosphorous

The amount of available phosphorus (P) from acidic soil (pH > 7) was determined by Bray 1 method (Bray & Kurtz, 1945).

Principle

Monocalcium phosphate and other acid soluble forms of P are extracted using Hydrochloric acid (HCl) and NH_4F. The fluoride ion has the unique ability to mix with Al^{3+} and Fe^{3+} ions in acidic solutions, releasing the P that these ions were holding in the soil. The amount of accessible P that has been released into the soil solution is estimated calorimetrically.

$3NH_4F + 3HF + AlPO_4$	=	$H_3PO_4 + (NH_4)_3AlF_6$
$3NH_4F + 3F + FePO_4$	=	$H_3PO_4 + (NH_4)_3FeF_6$

Materials required

(i). 0.5 M NaHCO3 (pH 8.5): 42 g of NaHCO3 dissolved in 1 litre of water, (ii). Darco G. 60 or activated carbon (free of phosphorous), (iii). Ascorbic acid,

(iv). Reagent A

a. Dissolve 12 g of ammonium molybdate in 250 ml of distilled water.
b. Dissolve 0.291 g of antimony potassium tartrate in 100 ml of water.
c. Prepare 1000 ml of 5N H_2SO_4 (138 ml of conc.H_2SO_4 made up to 1 litre). Mix the above three reagents well and make up the volume to 2 litres.

(v). Reagent B

* 1.056 g of ascorbic acid dissolved in 200 ml of reagent A. (prepare reagent B freshly every time).

(vi). Shaking bottle 100 ml, (vii) Mechanical shaker, (viii) pipette, (ix). volumetric flask 25 ml (x) Filter paper No.40, and (xi). photoelectric colourimeter.

Procedure

A 5 g of soil was weighed and placed in a 100 ml polythene shaking bottle. 50 ml of Bray No.1 extractant was added. For one minute, the contents were shaken in a reciprocatory mechanical shaker. Whatman No. 40 filter paper was used to filter the contents. Concurrently, I ran a blank. Pipette 5 ml of the filtrate into a 25 ml volumetric flask and add 4 ml of reagent B to make up the volume to 25 ml. Shake the contents for colour development and use a spectrophotometer (UV- Vis Spectrophotometer, model: Evolution 201, serial number: 5A4T146001) to detect the colour intensity at 660 nm.

Weight of the soil taken	=	20 g
Volume of N/50 H_2SO_4 used	=	X ml (Titre value)
1 ml of N/50 H_2SO_4	=	0.00028 g Nitrogen
X ml of N/50 H_2SO_4	=	0.00028 x X g N
In 20 g of soil, this is present.		
Therefore, N present in kg ha^{-1}	=	$\frac{0.00028\ (X)\ 2 \times 10^6}{20}$

Preparation of standard curve

Primary standard

Potassium dihydrogen phosphate (KH_2PO_4) is dried at 40 ^{0}C and 0.2195 g of it is dissolved in 400 ml of distilled water. Then 25 ml of 1N H_2SO_4 is added and volume made up to 1000 ml. This gives 50 ppm of P. The addition of H_2SO_4 enhances the storage life of the standard solution.

Secondary standard

100 ml of the 50 ppm stock solution is diluted to 1000 ml. This gives 5 ppm of P. From these ten concentrations of P were prepared (Table 3.3).

Table 3.3. Various dilutions of concentrations from P stock solution for preparing standard curve

Concentration required	Volume to be pipette out from 5 ppm stock solution	Volume to be made up to
0.1 ppm	0.5 ml	25 ml
0.2 ppm	1.0 ml	25 ml
0.3 ppm	1.5 ml	25 ml
0.4 ppm	2.0 ml	25 ml
0.5 ppm	2.5 ml	25 ml
0.6 ppm	3.0 ml	25 ml
0.7 ppm	3.5 ml	25 ml
0.8 ppm	4.0 ml	25 ml
0.9 ppm	4.5 ml	25 ml
1.0 ppm	5.0 ml	25 ml

(Source: rvskvv.net)

5 ml of Bray No.1 extractant was added to the P solutions. 4 ml of reagent B was added. Distilled water was used to make up a volume of 25 ml. Filled the photoelectric colourimeter with the contents and recorded the percent transmittance. Draw the curve by plotting the % transmittance against the concentration of P. The concentration of P in the soil extract was determined using this standard curve.

3.1.4.7. Available potassium

The neutral n ammonium acetate (N NH_4OAc) is used to extract the available potassium in the soil. With a flame photometer, the potassium content of the soil was measured (Stanford & English, 1949).

Principle

The K ions in the exchange sites are replaced with NH_4^+ which releases K^+. The concentration of K ions in the solution is then determined using Flame photometer.

Materials required

(i). 1N ammonium acetate (neutral in pH): Dissolve 77 g of AR grade ammonium acetate (CH_3COONH_4) in 1000 ml of distilled water. Adjust the pH to 7.0, (ii). Injection vials, (iii). Filter paper No.40, (iv). Funnel and (v). Flame photometer.

Procedure

5 g soil was transferred to a 100 ml shaking bottle. 25 ml of 1N ammonium acetate was added, and the contents were shaken for 5 minutes in a mechanical reciprocating shaker. Whatman no.40 filter paper was used to filter the contents. Feed the filtrate into the flame photometer, record the reading, and then use a standard curve to calculate the available K content.

Calculation

Weight of soil taken	=	5 g
Volume of extractant used	=	25 ml
Flame photometer reading	=	T
Concentration of K in the standard curve for T	=	X ppm
	=	X microgram/ml
	=	X/ 10^6 g/ml
Therefore in 25 ml of solution	=	X/10^6 x 25 g
This is the amount of K present in 5 g of soil		
Therefore, available K in soil in kg ha^{-1}	=	$\frac{X}{10^6}$ x $\frac{25}{5}$ x 2 x 10^6

Preparation of standard curve

Dissolved 1.907 g of AR grade KCl in one litter of water. The resulted 1000 ppm of K (1000 mg/ ml). 100 ml of 1000 ppm K is diluted to one litre which gives 100 ppm K. From this main stock solution, nine standards ranging from 10 to 100 ppm was prepared (Table 3.4).

Recorded the flame photometer reading for the above K solutions and plotted the meter reading against the corresponding concentration of K. Used this standard curve for finding out the concentration of K in the soil extract.

Table 3.4. Various dilutions of concentrations from potassium stock solution for preparing standard curve

Concentration required	Volume to be pipette out from 100 ppm stock solution	Volume to be made up to
10 ppm	10 ml	100 ml
20 ppm	20 ml	100 ml
30 ppm	30 ml	100 ml
40 ppm	40 ml	100 ml
50 ppm	50 ml	100 ml
60 ppm	60 ml	100 ml
70 ppm	70 ml	100 ml
80 ppm	80 ml	100 ml
90 ppm	90 ml	100 ml

(Source: rvskvv.net)

3.1.5. Irrigation

The AWD approach involved periodically flooding a rice field to a depth of approximately 5 cm, allowing the field to dry until the water level reached a specific moisture threshold, i.e., 30 % soil moisture (fixed as per the site requirement), before reinitiating flooding (Fig.3.6a). In the initial stages, during the vegetative phase, the field was flooded to a depth of 3 cm and allowed to dry until the moisture content fell below the designated threshold. Subsequently in the next stages, the field was flooded again, this time to a depth of 5 cm. This cyclic irrigation pattern, alternating between flooded and non-flooded drying cycles, persisted throughout the rice crop growing season. However,

an exception was made one week before to one week after flowering, during which a ponded water depth of 5 cm above the soil was maintained to prevent water stress, a condition that could lead to significant yield losses. The AWD cycle was sustained beyond the flowering stage, extending into the grain filling and ripening phases. The soil moisture was permitted to decrease to 30 % before initiating the next flooding, referred to as 'Safe AWD irrigation' (Bouman et al., 2007). In this experimental field, we standardized the interval between two irrigations in the AWD method to 3 days until the appearance of soil cracks (see Fig.3.7). The duration between irrigations was contingent on factors such as soil type, rainfall, weather conditions affecting ET_C (crop evapotranspiration), soil moisture levels, and the growth stage of the rice crop.

The ideal conditions for rice development are often those that involve constant flooding of water (Fig.3.6b). Water levels should start out at about 3 cm after transplanting and progressively rise to 5–10 cm (depending on the height of the plants). They should stay there until the field is emptied 7–10 days before harvest.

a b

Fig.3.6. Lysimeter setup for (a) AWD and (b) Flooded/ water-logged irrigation methods

Fig.3.7. Cracks appeaser in the soil between two irrigation events in the AWD irrigation method

3.1.6. Crop management

3.1.6.1. Application of manures and fertilizers

During the time of land preparation, farm yard manure (FYM) was applied to the field at a rate of 5000 kg ha $^{-1}$. Fertilizers were applied to the crop as per the recommendation in the package of practices (KAU, 2016). For medium duration 110 N: 45 P_2O_5: 45 K_2O kg ha^{-1} has been recommended. The recommended doses of fertilizers were applied using fertilizers like urea for N, mono ammonium phosphate (MAP) for P and muriate of potash (MUP) for potassium (K). 131.93 g of Urea for N2 treatment and 158.32g for N3 treatment were applied in the experimental plot in three different stages of paddy growth, first during the basal preparation, then during the tillering stage and then during the panicle initiation stage. N1 treatment had no N input hence, the rest of the nutrients i.e. phosphorus and potassium were applied in all experimental plots according to recommendations (see Table 3.5). The entire dose of P, a half dose of potassium was given as basal application while the remaining half dose potassium was top dressed during panicle the initiation stage. The detailed nutrient distribution in the experimental plot is in Table 3.5.

Table 3.5. Nutrients distribution in the experimental plot

Treatment	Urea (g)			MAP (g)			MOP (g)		
	BA	AT	API	BA	AT	API	BA	AT	API
N2	43.98	43.98	43.98	44.26	-	-	22.5	-	22.5
N3	52.77	52.77	52.77	44.26	-	-	22.5	-	22.5
				SSP (g)					
N1	-	-	-	205.00	-	-	22.5	-	22.5

Where, N1- 0 % N application of the recommended dose of nutrients through inorganic fertilizers; N2- 100 % N application of the recommended dose of nutrients through inorganic fertilizers: NF3- 120 % N application of the recommended dose of nutrients through inorganic fertilizers; MAP- Mono ammonium phosphate; MOP- Muriate of potash; SSP- Single Super Phosphate; BA- Basal application; AT- At tillering; API- At panicle initiation

3.1.6.2. After planting

To control the weeds a hand-weeding was carried out After transplanting hand weeding was practiced throughout the crop period. Proper control measures through Integrated pest management -IPM (Nimbicidin, Pheromone trap, and mixture of chilly, ginger, pepper, and a sticking agent like soap) were undertaken to protect the crop from pests and diseases. All 19 (19N: 19P: 19K) was sprayed at 0.1 % twice a week up to two months after transplanting.

3.1.7. Observations

Field observations were taken in the three different growth stages of the crop, i.e., tillering, flowering, and maturity. In order to take the observations three plants have been selected randomly from each plot avoiding the border plants at different developmental stages of rice, i.e., tillering (30 days after transplanting (DAT)), flowering (60DAT), and maturity (105 DAT) and tagged. Biometric, physiological and yield parameters of these plants were observed.

Biometric characters

3.1.7.1. Plant height

Plant height at regular intervals was noted using a meter scale in centimetres. The height of the plants from the base/ above the ground level to the tip of the longest leaf has been recorded for all five observational plants in each plot.

3.1.7.2. Number of tillers

The total number of tillers were counted from the base and expressed as numbers.

3.1.7.3. Leaf area index

The leaf area of the flag leaf was found out by direct method using the given formula by measuring the length and maximum width (middle portion) of the flag leaf. Also measured by the graphical method by sketching the outline of the leaf on graph paper and calculated its area (Tanko & Hassan, 2016).

$$\text{LAI} = \frac{\text{L} \times \text{W} \times \text{K} \times \text{No. of leaves plant}^{-1}}{\text{Land area occupied by plant}}$$

Where, L - Length of leaf (cm)

K - Correction factor (0.75)

W - Width of leaf (cm)

3.1.7.4. Number of panicles

The number of panicles per plant were counted.

3.1.8. Determination of water input

Total water input was measured in both water management treatments. Total water input comprised both irrigation and rainfall. In both treatments, irrigation water volume was inputted to each plot by adding the water supplied through the irrigation pipeline, while rainfall data were collected from the CWRDM meteorological yard. If there is enough rain, the demand for daily watering can be reduced. There is no need for further irrigation when there has been adequate rainfall and the land has acquired moisture from the rain. As a result, rain can immediately contribute to water conservation. When rainfall effectively hydrates the soil, the need for extra irrigation water is reduced. This can result in less overall water input on rainy days.

$$Water\ saving(\%) = \frac{water\ input\ in\ CF\ sytem - water\ input\ in\ AWD\ system}{Water\ input\ in\ CF\ system} \times 100$$

3.1.9. Statistical analysis

Statistical analysis such as two-factor ANOVA and post-hoc (Fisher's Least Significant Difference- LSD) were accomplished using GRAPES software (Gopinath et al., 2021). Wherever the treatment differences were significant, the critical difference was worked out at a 5 per cent and 10 per cent probability level. The non-significant treatment difference is denoted by NS.

3.2. *Experiment -2*

Evaluation of nutrient management and method of planting on crop productivity of aerobic rice and estimating the water saving in aerobic using FAO-CROPWAT model

This experiment was designed to evaluate different nutrient management practices and methods of planting with respect to aerobic rice production in addition, an attempt was made to quantify the water saving under aerobic rice and the methodology for this experiment is detailed hereunder.

3.2.1. Design and Layout

The experiment was carried out during the *Viruppu* season of 2019 with randomized block design (RBD) on direct planted and transplanted aerobic rice with the *Uma rice cultivar* in the experimental field of Land and Water Management Research Group Division at Centre for Water Resources Development and Management (CWRDM), Kunnamangalam, Kozhikode, Kerala, India (Fig.3.8). The Regional Agriculture Research Station in Pattambi, Kerala, provided the rice seed. Before the experiments, soil chemical analysis was done to determine the soil physicochemical properties. The treatments that were attempted are given the Table 3.6. It consisted of (1) method of planting, which consists of (a) Direct Seeding Rice (DSR) - P1, a system of rice growing in which rice seeds are sown directly in fields without going through a nursery stage or being transplanted, and (b) transplanting – P2; and (2) nutrient management practice treatment, which consists of applying (a) 125 % of inorganic fertilizers -T1, (b) 100 % of inorganic fertilizers -T2, and (c) 100 % of organic manures -T3. Twenty-five days old seedlings were transplanted with a spacing of 20 cm x 15 cm in the experimental plots. The recommended dose of fertilizers (NPK) was applied to the plots as per the treatment schedule (KAU, 2016). All the local cultural and management practices were adopted as per the package of practices of Kerala Agricultural University (KAU, 2016). The experiment comprised six treatments with six replications and was conducted in non-puddled soil.

Table 3.6. Experiment 2- treatment details

Treatments	
Method of planting	**Nutrient levels**
P1- Direct seeding of rice (DSR)	T1 – 125 % of inorganic fertilizers
P2- Transplanted	T2 – 100 % of inorganic fertilizers
	T3 – 100 % of organic manures

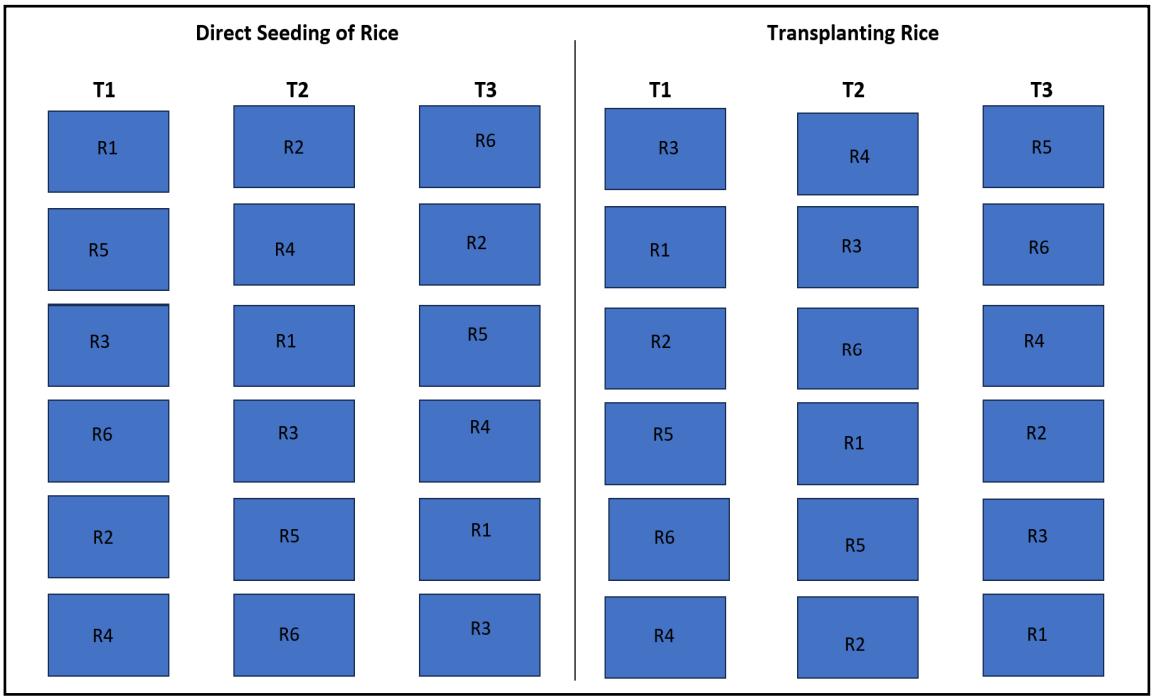


Fig.3.8. Experiment 2 - diagrammatic representation of experimental field

(T1 – 125 % of inorganic fertilizers, T2 – 100 % of inorganic fertilizers and T3 – 100 % of organic manures)

3.2.2. Variety

Uma (MO 16) is the rice variety used in this experiment. Detailed procedure is already explained section 3.1.2.

3.2.3. Climatic parameters.

Different climatic parameters namely, minimum temperature, maximum temperature, rainfall, minimum relative humidity, maximum relative humidity, solar radiation, and pan evaporation were measured throughout the crop period from the meteorological observatory of CWRDM.

3.2.4. Soil Characters

Soil samples were randomly gathered from experimental fields, encompassing two distinct depths: 0 to 15 cm and 15 cm to 30 cm. Subsequently, these samples underwent analysis to determine their physicochemical attributes, along with the available concentrations of nitrogen (N), phosphorus (P), and potassium (K), employing the methods outlined below. The collected samples were subjected to shade-drying, followed by pulverization and sieving through a 2 mm sieve, and then analysed for selected nutrients.

Soil Physicochemical properties

3.2.4.1. Bulk density

Bulk density, also known as apparent density, is the ratio of soil mass to total volume, including air space and organic elements. It is calculated using the oven dry weight of a unit volume of soil and represented in mg m^{-3}. The soil's bulk density is assessed by taking a disturbed chunk of soil with a cylindrical core (Gupta & Dakshinamoorthy, 1981). The bulk density was calculated as the volume of the core and the weight of the soil by using the following formula.

Principle

The bulk density and percent pore space are calculated using the apparent and actual volumes of soil measured by adding a known amount of water to a measuring cylinder containing a weighed quantity of soil.

Materials required

(i). Measuring cylinder (100 ml) with a glass stopper and (ii). Balance.

Procedure

Weighed 20 g of soil sample and gently tapped the cylinder to transfer small quantities at a time to a 100 ml measuring cylinder with a glass stopper. Noted the volume when the soil has been entirely transported. Using a pipette, add 50 ml of water around the walls of the cylinder until the entire soil mass is completely soaked. After that, the final volume of soil was noted. Keep the cylinder with soil and water undisturbed for at least 30 minutes to allow the entire pore area to fill with water and then final volume of soil plus water was recorded.

Calculation

Weight of the soil sample	=	W (20) g
Volume of the soil taken	=	V_1 ml
Volume of water added	=	V_2 ml
Volume of soil + water	=	V_1+V_2 ml
Volume of soil + water at the end of experiment	=	V_3 ml

Pore space volume = $(V_1+V_2) - V_3$ ml

Per cent pore space = $\frac{(V_1+V_2) - V_3}{V_1}$ x 100

Bulk density = $\frac{\text{wt.of soil}}{\text{vol.of soil}}$ g/cc

3.2.4.2. Particle density

Particle density and total porosity are measured through the cylinder method (Gupta & Dakshinamoorthy, 1981). Porosity is that fraction of soil volume excluding pore space. For a detailed procedure is explained in section 3.2.4.1.

$$Particle\ density = \frac{Weight\ of\ the\ soil}{Soil\ volume - Pore\ space\ volume}$$

3.2.4.3. Field capacity

Field capacity is the soil's ability to retain water once extra liquid has been removed and the velocity of downward movement has slowed. It is often expressed as a percentage of the soil's dry weight. Field capacity is the maximum amount of water that can be used by plants since it provides the best absorption of nutrients and water. A pressure plate apparatus was used to apply a suction of -1/3 atmosphere to a saturated soil sample in order to determine field capacity. Detailed procedure is already explained section 3.1.4.1.

3.2.4.4. Permanent wilting point

The minimum amount of water in the soil that a plant needs to avoid wilting is known as the PWP. When a plant runs out of water, it reaches the permanent wilting point, which is typically at 15 bars. Even though there is still some water in the soil at this point, the roots are finding it challenging to draw it up. Detailed procedure is already explained section 3.1.4.1.

3.2.4.5. Soil pH

Soil pH was measured using 1:2.5 ratio soil-water suspension with the glass electrode (Jackson ,1973) using the Eutech pH & electrical conductivity meter (model number PC 510; serial number: 2237098).

3.2.4.6. Soil organic carbon

Soil organic carbon was measured through a chromic acid wet digestion method (Walkley & Black, 1934). Detailed procedure is already explained section 3.1.4.4.

3.2.4.7. Available nitrogen

The amount of available soil nitrogen in the soil sample was determined by the alkaline permanganate method proposed by Subbiah & Asija, 1956 (As described in section 3.1.4.5).

3.2.4.8. Available phosphorous

The amount of available soil P from the soil was extracted with Bray I extractant (0.025 N HCl + 0.03 N NH_4F) Blue colour was developed using ascorbic acid as reductant and the colour intensity was measured at 660 nm with a spectrophotometer (UV- Vis Spectrophotometer, model: Evolution 201, serial number: 5A4T146001) (Bray & Kurtz, 1945) (As explained in section 3.1.4.6).

3.2.4.9. Available potassium

Neutral ammonium acetate (N NH_4OAc) was used to extract the available potassium in the soil. The soil available potassium concentration was measured in a flame photometer (Stanford & English, 1949). Detailed procedure is already explained section 3.1.4.7.

3.2.5. Crop management

3.2.5.1. Application of manures and fertilizers

During the time of land preparation, FYM was applied to the field at a rate of 5000 kg ha $^{-1}$. Fertilizers were applied to the crop as per the recommendation in the package of practices (KAU, 2016). For medium duration 110 N: 45 P_2O_5: 45 K_2O kg ha^{-1} has been recommended. The recommended doses of fertilizers were applied using fertilizers like urea for N, mono ammonium phosphate (MAP) for P and muriate of potash (MUP) for K. Urea was applied in the experimental plot in three different stages of paddy growth, first during the basal preparation, then during the tillering stage and then during the panicle initiation stage. The entire dose of P and a half dose of potassium was given as basal application while the remaining half dose potassium was top dressed during the panicle initiation stage. For organic manure, slight adjustments were made concerning P and K so

that N application was common as per the treatments. The detailed nutrient distribution in the experimental plot is in Table 3.7.

Table 3.7. Nutrients distribution in the experimental plot

Treatment	Urea (g)			MAP (g)			MOP (g)		
	BA	**AT**	**API**	**BA**	**AT**	**API**	**BA**	**AT**	**API**
T1	54.98	54.98	54.98	55.33	-	-	28.13	-	28.13
T2	43.98	43.98	43.98	44.26	-	-	22.5	-	22.5
	Compost			**Organic NPK (ml)**					
T3	420.00	420.00	420.00	0.75		0.75		0.75	

Where, T1- 125 % of inorganic fertilizers; T2- 100 % of inorganic fertilizers; T3- 100 % of organic manures; MAP- Mono ammonium phosphate; MOP- Muriate of potash; BA - Basal application; AT - At tillering; API - At panicle initiation

3.2.5.2. After planting

To control the weeds a hand-weeding was carried out. After transplanting hand weeding was practiced throughout the crop period. Proper control measures through Integrated pest management -IPM (Nimbicidin, Pheromone trap, and mixture of chilly, ginger, pepper, and a sticking agent like soap) were undertaken to protect the crop from pests and diseases. All 19 (19N: 19P: 19K) was sprayed at 0.1 % twice a week up to two months after transplanting.

3.2.6. Observations

Field observations were taken in the three different growth stages of the crop, i.e., tillering, flowering, and maturity. In order to take the observations five plants have been selected randomly from each plot avoiding the border plants at four different developmental stages of rice, i.e., tillering (30^{th} day), flowering (50^{th} day), maturity (85^{th} day) and harvest (115^{th} day) were tagged. Biometric, physiological and yield parameters of these plants were observed.

Biometric characters

3.2.6.1. Plant height

Plant height at regular intervals was noted using a meter scale in centimetres. The height of the plants from the base/ above the ground level to the tip of the longest leaf has been recorded for all five observational plants in each plot.

3.2.6.2. Number of tillers

The total number of tillers was counted from the base and expressed as numbers.

3.2.6.3. Grain yield

At the harvest grain yield of each plot has been recorded in kg ha $^{-1}$.

3.2.7. Irrigation using FAO-CROPWAT

Using FAO - CROPWAT (Fig.3.9) software, irrigation requirements and schedule were created for all three-rice growing season of Kerala, including for both aerobic and anaerobic cropping. Equation (1) illustrates how the FAO Penman-Monteith approach (Doorenbos & Kassam 1979; Allen et al., 1998; Surendran et al., 2015, 2017) was used to compute the irrigation quantity.

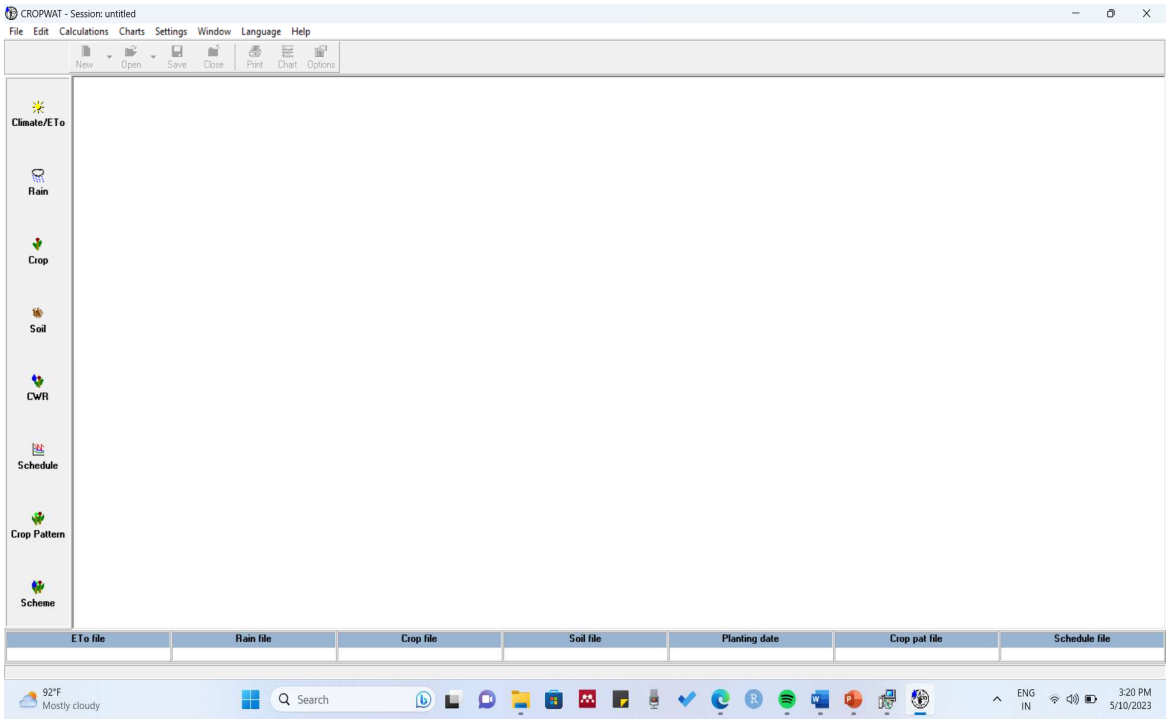


Fig.3.9. Home page of FAO CROPWAT software

$$\mathrm{ETo} = \frac{0.408\Delta(Rn - G) + \Upsilon\frac{900}{T + 273}u_2(e_s - e_s)}{\Delta + \Upsilon(1 + 0.34\,u_2)}$$

..... (1)

ET_o- Reference crop evapotranspiration (mm day^{-1})

Rn - Net radiation at the crop surface (MJ m^{-2} day^{-1})

G - Soil heat flex density (MJ m^{-2} day^{-1})

T- Mean daily air temperature at 2m height (^oC)

u_2 - Wind speed at 2 m height (ms^{-1})

e_s- Saturation vapour pressure (Kpa)

e_a- Actual vapour pressure

e_s-e_a- Saturation vapour pressure deficit (Kpa)

Δ – Slope vapour pressure curve [Kpa (^oC)]

γ – Psychrometric constant [Kpa (^oC)]

The climatic parameters used for the determination of ET_o are maximum temperature and minimum temperature in ^oC, maximum relative humidity and minimum relative humidity in %, wind speed in km/day, solar radiation/ sunshine hours in hr, latitude, longitude and altitude (in m) observed from the CWRDM meteorological observatory of experimental filed. ET_0 was determined for every ten days during the entire experimental period using long-term historic climatic data (1983 to 2019). Crop evapotranspiration (ET_C) per decade is calculated by multiplying ET_0 by the crop coefficient values (K_c) taken from available published data (Surendran et al., 2017). The total water requirement was calculated as per equation 2.

$$WR = ET_c + Application\ Lossess + Special\ Needs \quad \text{--- (2)}$$

Where, WR –Water Requirement of crops

ET_C - Crop Evapotranspiration

Special needs – such as land preparation in the case of paddy

Percolation water losses for anaerobic and aerobic rice were assigned as 6 mm/day and 2 mm/day, respectively (Surendran et al., 2017). In addition, 300 mm and 200 mm of water required for the land preparation activities for anaerobic and aerobic rice, respectively. According to equation 3, net irrigation demand, also known as net irrigation requirement (NIR), was calculated by deducting the amount of crop water required from

the effective rainfall obtained during the crop growth period and, if any, groundwater contribution.

$$NIR = WR - ER - Ge \ldots\ldots (3)$$

Were, ER- Effective rainfall

Ge –Ground water contribution from water table (not considered in the calculation as this is negligible)

The amount of rainfall that is effectively utilized by the crop is known as effective rainfall, or ER (P_{eff}). After a heavy rainfall, some water is lost by surface runoff and deep percolation. Therefore, CROPWAT 8.0 provides four methods—a set percentage, reliable rain, empirical formula, and USDA Soil Conservation Service methods to account for losses resulting from runoff or percolation. The USDA Soil Conservation Service approach was chosen for this investigation.

$$P_{eff} = P_{month}\, x\, (125 - 0.2\, x\, P_{month})/125\ for\ P_{month} \leq 250m$$

$$P_{eff} = 125 + 0.1\, x\, P_{month}\ for\ P_{month} > 250m$$

Were,

P_{month} = Monthly rainfall and

P_{eff}= Effective rainfall

3.2.8. Simulating the water saving of aerobic rice

Simulation research was done to estimate the water-saving benefits of aerobic rice farming compared with conventional flood rice growing i.e. anaerobic rice cultivation. Using the CROPWAT model, the net irrigation needs and total crop water requirement for each of all three rice-growing seasons of Kerala were determined. The *Virippu* season/ Autumn season is the first crop season, which starts in April - May and extends up to September – October. The second season is the *Mundakan* season/ Winter season, which starts in September - October and extends up to December - January. The third crop season is the *Puncha* season/ Summer season, which starts in December - January and extends up to March – April. Data sets pertaining to rice farming, such as the total area planted with rice, and the amount of rice produced, etc. of Kozhikode districts for the past thirty years were collected from the Department of Economics and Statistics data (DoES, 2023). The FAO CROPWAT model 8.0 was utilized to determine the total water need based on the area under rice cultivation, considering both aerobic and flooded conditions, as previously

mentioned. (Surendran et al., 2017). Based on the assumption that the flooded area has been converted to an aerobic farming method, these data were compared with respect to water saving.

3.2.9. Statistical analysis

Statistical data analysis - two-factor ANOVA and post hoc (LSD) were carried out using average values, and standard error using GRAPES software (Gopinath et al., 2021). Wherever the treatment differences were significant, the critical difference was worked out at a 5 per cent and 10 per cent probability level. The non-significant treatment difference is denoted by NS.

3.3. *Experiment -3*

Assessing the different levels of water and nutrient application on growth and productivity of rice under aerobic cultivation

This third experiment was designed to evaluate the effect of different levels of water and nutrient management practices on aerobic rice yield. During the field experiment, the leaf rolling phenomenon was observed in some patches of the experimental plot irrespective of the irrigation treatments carried out. Hence, a brief study was conducted to identify the management strategies for the leaf-rolling issue in paddy and to understand its leaf-rolling behaviour under different moisture-absorbing mediums. The detailed methodology for this experiment is detailed hereunder.

The experimental design was a randomized block design (RBD) conducted during the summer (*Puncha*) season of 2020 (January to April), on aerobic rice with the *Uma* rice variety in the field of Land and Water Management Research Group Division at the CWRDM, Kunnamangalam, Kozhikode, Kerala, India. The Regional Agriculture Research Station in Pattambi, Kerala, provided the rice seed. The first one is the experiment we planned to evaluate irrigation and nutrient management practices under aerobic rice and during the experiment, we noticed a leaf-rolling phenomenon in the plots. Hence, to understand the leaf rolling pattern and effective soil moisture management practices a sub-experiment was held with a set of moisture absorbent media mixed with the soil as treatments. The third experiment was conducted to analyse the leaf rolling with soil alone and along with moisture absorbent media and recovery pattern using videography in a pot culture experiment. The details of individual experiments are described hereunder.

3.3.1. Field experiment

3.3.1.1. Design and Layout

The first experiment has a randomized block design (RBD). Different irrigational and nutrient management were attempted (Table 3.8). Two irrigation management practices were selected. They were 1. 100 % ET_C (I1) and 2. 120 % ET_C (I2). Three different nutrient management practices were opted for. These were comprised of 1. 75 % recommended dose of N and 100% P & K application of inorganic (IO) fertilizers(T1); 2. 100 % recommended dose of NPK application of inorganic (IO) fertilizers (T2); 3. 125 % recommended dose of N and 100% of P & K application application of inorganic (IO) fertilizer (T3). A recommended dose of fertilizers (KAU, 2016) was applied and the exact quantities of nutrients were applied to the individual treatments based on the nutrient content present in the inorganic fertilizers. The dosage was applied at three stages, 1/3 % dose at bed preparation, 1/3 % dose of N at maximum tillering stage and the remaining 1/3 % dose at panicle initiation stage, as per the package of practices recommendations of KAU. All the cultural and management practices were adopted as per the package of practices of Kerala Agricultural University (KAU, 2016). The experiment comprised six treatments with five replications and was conducted in puddled soil. According to the package of practices recommendation the field has been ploughed well to bring fresh nutrients the surface and to incorporate the stubbles. After that, the land was puddled and then the experimental field was divided into plots as per the layout of the field (Fig.3.10). Nursery was maintained near to the experimental field (Fig.3.11) and transplanting was done on the twenty-first day of plating (Fig.3.12 & Fig.13) as per the spacing recommended (20 cm X 10 cm) in the package of practices (KAU, 2016) (Fig.3.14). 9.5 m^2 (2.5 m X 3.8 m) was the area of each plot.

Table 3.8. Experiment 3- treatment details

Treatments	
Irrigation levels	**Nutrient levels**
I1- 100 % ET_C	T1 - 75 % Recommended dose of N and 100% P & K application
I2- 120 % ET_C	T2 - 100 % Recommended dose of NPK application
	T3 – 125 % Recommended dose of N and 100% of P & K application

3.3.1.2. Climatic parameters.

Different climatic parameters namely, minimum temperature, maximum temperature, rainfall, minimum relative humidity, maximum relative humidity, solar radiation, and pan evaporation were measured throughout the crop period from the meteorological observatory of CWRDM.

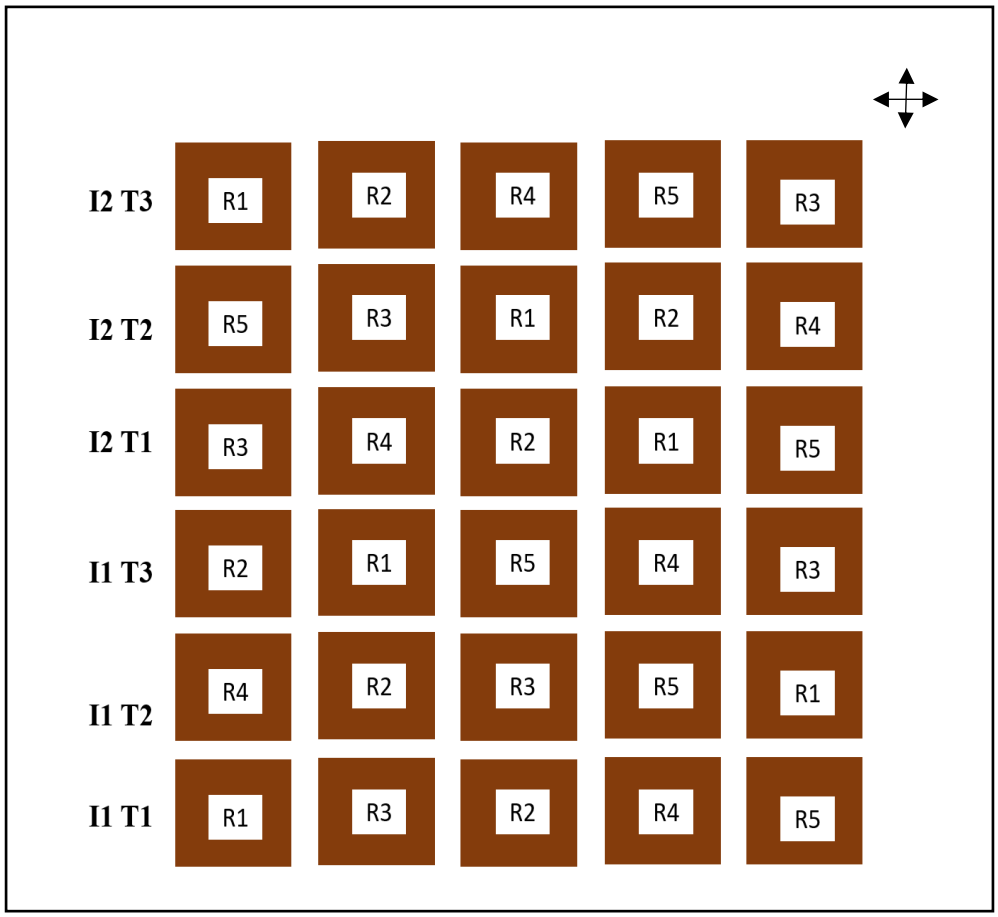


Fig. 3.10. Experiment 3- diagrammatic representation of experimental field

(I1- 100 % ET_C ; I2- 120 % ET_C ; T1 - 75 % of N application of inorganic fertilizers; T2 - 100 % N application of inorganic fertilizers; T3 - 125 % N application of inorganic fertilizers)

Fig.3.11. Nursery maintenance of rice for the transplantation

Fig.3.12. Images of seedling and transplantation of seedling from nursery to experimental field.

Fig.3.13. Transplanted experimental field

Fig.3.14. Experiment plot at tillering stage

3.3.1.3. Soil Characters

soil samples were collected from experimental fields at random for a depth of 0 to 15 cm and 15 cm to 30 cm and analysed for physio-chemical characteristics as per the standard methods mentioned below.

3.3.1.3.1. Soil pH

Soil pH was measured using 1:2.5 ratio soil-water suspension with a glass electrode (Jackson ,1973) using the Eutech pH & electrical conductivity meter (model number PC 510; serial number: 2237098).

3.3.1.3.2. Soil organic carbon (SOC)

SOC was measured through the chromic acid wet digestion method (Walkley & Black, 1934). Detailed procedure is already explained section 3.1.4.4.

3.3.1.3.3. Available nitrogen

The amount of available soil nitrogen in the soil sample was identified by the alkaline permanganate method (Subbiah & Asija, 1956). Detailed procedure is already explained section 3.1.4.5.

3.3.1.3.4. Available phosphorous

The amount of available P from the soil was extracted with Bray I extractant (0.025 N HCl + 0.03 N NH_4F) Blue colour was developed using ascorbic acid as reductant and the colour intensity was measured at 660 nm with a spectrophotometer (UV- Vis Spectrophotometer, model: Evolution 201, serial number: 5A4T146001) (Bray & Kurtz, 1945). Detailed procedure is already explained section 3.1.4.6.

3.3.1.3.5 Available potassium

Neutral normal ammonium acetate (N NH_4OAc) is used to extract the available potassium in the soil. The soil available potassium concentration was read in a flame photometer (Stanford & English, 1949). Detailed procedure is already explained section 3.1.4.7.

3.3.1.4 Crop management

3.3.1.4.1. Application of manures and fertilizers

During the time of land preparation, FYM was applied to the field at a rate of 5000 kg ha $^{-1}$. Fertilizers were applied to the crop as per the recommendation in the package of practices (KAU, 2016). For medium duration 110 N: 45 P_2O_5: 45 K_2O kg ha^{-1} has been recommended. The recommended doses of fertilizers were applied using fertilizers like urea for N, mono ammonium phosphate (MAP) for P and muriate of potash (MUP) for

potassium (K). Urea was applied in the experimental plot in three different stages of paddy growth, first during the basal preparation, then during the tillering stage and then the during panicle initiation stage. The entire dose of P and a half dose of potassium were given as basal application while the remaining half dose of potassium was top dressed during the panicle initiation stage. For organic manure, slight adjustments were made concerning P and K so that N application was common as per the treatments. The detailed nutrient distribution in the experimental plot is in Table 3.9.

Table 3.9. Nutrients distribution in the experimental plot

Treatment	Urea (g)			MAP (g)			MOP (g)		
	BA	AT	API	BA	AT	API	BA	AT	API
T1	32.99	32.99	32.99	44.26	-	-	22.5	-	22.5
T2	43.98	43.98	43.98	44.26	-	-	22.5	-	22.5
T3	54.98	54.98	54.98	44.26	-	-	22.5	-	22.5

Where, T1 - 75 % of N application of inorganic fertilizers; T2 - 100 % N application of inorganic fertilizers; T3 - 125 % N application of inorganic fertilizers; MAP- Mono ammonium phosphate; MOP- Muriate of potash; BA - Basal application; AT - At tillering API - At panicle initiation

3.3.1.4.2. After planting

To control the weeds a hand-weeding was carried out. After transplanting hand weeding was practiced throughout the crop period. Proper control measures through Integrated pest management -IPM (Nimbicidin, Pheromone trap, and mixture of chilly, ginger, pepper, and a sticking agent like soap) were undertaken to protect the crop from pests and diseases. All 19 (19N: 19P: 19K) was sprayed at 0.1% twice a week up to two months after transplanting.

3.3.1.4.3. Irrigation using FAO-CROPWAT

Irrigation was scheduled with the help of FAO- CROPWAT software. Detailed procedure is already explained section 3.2.7.

3.3.1.4.4. Observations

Field observations were taken in the three different growth stages of the crop, i.e., tillering, flowering, and maturity. In order to take the observations five plants have been selected randomly from each plot avoiding the border plants at four different developmental stages of rice, i.e., tillering (30th day) and maturity (85th day) were tagged. Biometric, physiological and yield parameters of these plants were observed.

Biometric characters

3.3.1.4.4.1. Plant height

Plant height at regular intervals weas noted using a meter scale in centimetres. The height of the plants from the base/ above the ground level to the tip of the longest leaf has been recorded for all five observational plants in each plot.

3.3.1.4.4.2. Number of tillers

Total number of tillers was counted from the base and expressed as numbers.

Yield parameters

3.3.1.4.4.3. Number of panicles/ tiller

The number of panicles per plant was counted.

3.3.1.4.4.4. Panicle length/ tiller

Panicles from each plot were selected at random and the length of the panicles was measured from the point of attachment on the stem to the tip of the panicle and expressed in cm.

3.3.1.4.4.5. Number of spikelets/ panicle

The number of spikelets in a panicle was recorded after harvesting. The panicles are collected randomly from the five observational plants.

3.3.1.4.4.6. Number of hollow spikelets/ panicle

The number of hollow spikelets in a panicle was recorded after harvesting. The panicles are collected randomly from the five observational plants.

3.3.1.4.4.7. Number of filled grains/ panicle

The number of filled grains in a panicle was recorded from panicles that were collected randomly from the five observational plants.

3.3.1.4.4.8. Weight of Thousand grains

Cleaned, dry 1000 grains were counted and then the weight of 1000 grains were observed in grams.

3.3.1.4.4.9. Straw yield

Straw obtained during the harvest time was dried and then the dry weight was recorded in kg ha $^{-1}$.

3.3.1.4.4.10. Harvest Index

The harvest index was calculated by using the following formula and expressed in percentage (Beadle, 1987).

$$Harvest\ index\ (\%) = \frac{Grain\ yield}{Biological\ yield} \text{x } 100$$

Where, Biological yield = Grain yield + Straw yield

3.3.1.4.4.11. Grain yield

At the harvest grain yield of each plot has been recorded in kg ha $^{-1}$.

Physiological observations.

3.3.1.4.4.12. Chlorophyll content

Measured 1g of finely chopped plant sample, placing it in a clean mortar. Subsequently, the tissue was finely ground to a pulp by adding 20 mL of 80 % acetone. After centrifugation at 5000 rpm for 5 minutes, the resulting supernatant was carefully transferred to a 100 mL volumetric flask. The residue underwent additional grinding with 20 mL of acetone, followed by centrifugation, and the supernatant was combined with the previously collected solution. This process was iterated until the residue attained a colourless state.

The mortar and pestle were meticulously washed with 80 % acetone, and the resulting clear washings were gathered in the volumetric flask. The volume was adjusted

to 100 mL using 80 % acetone, and the absorbance of the solution was measured at 645, 663, and 652nm against a blank of the solvent (80 % acetone). Subsequently, the quantity of chlorophyll in the extract was calculated using the provided equations, expressed in milligrams of tissue:

$$mg\ of\ Chlorophyll\ a = 12.7(A_{663}) - 2.69(A_{645})\ X\ \frac{V}{1000\ X\ W}$$

$$mg\ of\ Chlorophyll\ b = 22.9(A_{645}) - 4.68(A_{663})\ X\ \frac{V}{1000\ X\ W}$$

$$Total\ Chlorophyll\ = 20.2\ (A_{645}) - 8.02\ (A_{663})\ X\ \frac{V}{1000\ X\ W}$$

Where, A = Absorbance at specific wavelengths

V = Final volume of chlorophyll extract in the 80 % acetone solution

W = Fresh weight of tissue extracted.

3.3.1.4.4.13. Photosynthetic rate

The photosynthetic efficiency of each plant was taken using the LSI-SD portable photosynthetic system (ADC Bio Scientific Ltd, Hoddesdon, UK, serial number: 34336) after one month of the plantation. Measurements were taken on a bright sunny day on fully expanded uppermost leaves from 9:00 to 11:30 am (Fig.3.15). Due to the inconvenience plants with smaller leaves and poor growth were not considered for study.

Fig.3.15. Measuring the photosynthetic rate of paddy using LSI-SD portable photosynthetic system

3.3.2. Leaf rolling experiment

Understanding the leaf rolling of Paddy and exploring its management options under aerobic rice

During the field experiment, the leaf-rolling phenomenon was observed in some patches of the experimental plot (Fig.3.16). After observation, a second experiment was planned, and these plots were again subdivided and a few soil amendments as moisture absorbents were applied to understand the changes in the leaf rolling pattern. Hence to understand the same, different moisture-absorbent growing media such as cocopeat, compost, sawdust and vermiculite were incorporated into the different micro plots of size (2 * 2 m) and replicated five times to understand the effect along with the control.

Fig.3.16. Leaf rolling in the experimental field

Observations

3.3.2.1. Soil water content

Volumetric Soil Water Content (SWC) (%) was measured using a soil moisture probe (Procheck Decagon Devices (Digital), Model no; PC4597, Made: USA). The experimental data were statistically analysed by analysis of variance method as suggested by Panse & Sukhatme (1954).

3.3.2.2. Relative water content

Water potential serves as a valuable indicator of the energy state of plant water and is particularly beneficial for understanding transport within the soil–plant-atmosphere continuum. It stands out as the most suitable gauge of water status when considering the physiological implications of cellular water deficiency. The process involved the collection and tagging of fresh samples from the newest and fully expanded leaves. These leaves were carefully cut into undamaged, small pieces, with each piece weighing 0.5 g on a precision weighing balance. Subsequently, the samples were immersed in water-soaked tubes for a 4-hour duration, allowing the determination of the turgid weight. After water absorption, the samples were transferred to Petri dishes and subjected to oven-drying at 80 °C for a full day, 24 hours, facilitating the determination of the dry weight. The Relative Water Content (RWC) was then calculated using the provided equation.

$$RWC = \left(\frac{fw - dw}{tw - dw}\right) x\ 100$$

Where, RWC= relative water content

fw= fresh weight;

dw= dry weight

tw= turgid weight

3.3.2.3. Membrane leakage

Assessing the extent of cell membrane damage caused by water stress can be conveniently gauged by measuring the leakage of electrolytes from the cells. Cell membranes represent one of the primary focal points affected by various plant stresses, and it is widely acknowledged that preserving their integrity and stability in the face of water stress is a crucial factor contributing to the overall drought tolerance of plants. To determine membrane leakage, fresh samples of leaves were collected in a polythene bag and labelled for each treatment. According to treatment samples were cut into 1 cm^2 size and weighed 0.5 g gave in weighing balance. Weighed samples were placed in test tubes containing distilled water for 4 hrs and initial EC was measured by a conductivity meter. After this, the solution was placed in a hot water bath at 110 ^{0}C for 30 minutes. Later final EC was measured by a conductivity meter. The EL was defined as follows:

$$ML = \left(\frac{L1}{L2}\right) x\ 100$$

Where, ML = Membrane Leakage

L_1=initial conductivity

L_2= Final conductivity

3.3.2.4. Spectral reflectance measurements to understand the water stress

Reflectance measurements were conducted using the ASD FieldSpec4 spectroradiometer (manufactured by ASD - Analytical Spectral Devices, Boulder, CO, USA) at distinct physiological stages of rice growth, including tillering, flowering, and maturity. This instrument is specifically engineered for field applications, designed to capture visible and near-infrared (VNIR) as well as short-wave infrared (SWIR) spectra. Compact, field-portable, and precise, the spectroradiometer boasts a spectral range of 350–2500 nm and an impressive data collection speed of 0.2 seconds per spectrum. Data were taken at a height of approximately 0.9 m above the canopy cover with a 25° field of view. Polytetra flouroethylene (PTFE) Spectralon reference panels were initially used to calibrate the apparatus. Each plot of spectral reflectance profiles ranges from 350 to 2500 nm, and each set of observations is obtained by averaging seven to twelve measurements. The spectral acquisition software (RS^3) was employed to control the ASD's operation, receive, and store the transmitted spectral data. Subsequently, data obtained from the instrument underwent processing using View SpecPro (version 6.2) software for splice correction, and the mean was calculated for different samples. For further analysis, various vegetative and water indices were computed using standard references, and the specific details are presented in Table 3.10.

Table 3.10. Different vegetation indices worked out in this study

Index	Abbreviations	Formulation	Reference
Normalized Difference Vegetation Index	NDVI	$\frac{\rho NIR - \rho Red}{\rho NIR + \rho Red}$	Rouse et al., 1973
Generalized Difference Vegetation Index	GDVI	$\frac{\rho NIR - \rho Green}{\rho NIR + \rho Green}$	Wu, 2014
Leaf Area Index	LAI	$0.45 * e^{NDVI}$	Boegh et al., 2002
Vegetation Index	VI	$\rho 810 / \rho 560$	Inoue et al., 2008

Ratio Vegetation Index/ Simple Ratio	RVI	$\rho NIR/\rho Red$	Barati et al., 2011
Green Ratio Index	GRI	$\rho 830/\rho 550$	Inoue et al., 2008
Direct Vegetation Index	DVI	$\rho NIR - \rho Red$	Tucker, 1979
Transformed Vegetation Index	TVI	$(NDVI+0.5)^{1/2}$	Dw et al., 1975
Green Chlorophyll Index	CI(G)	$(\rho NIR/\rho Green) - 1$	Gitelson et al., 2005
Red-edge Chlorophyll Index	CI(R)	$\left(\frac{\rho NIR}{\rho Rededge}\right) - 1$	Ahamed et al., 2011
Structure Insensitive Pigment Index	SIPI	$\frac{\rho 800 - \rho 445}{\rho 800 - \rho 680}$	Penuelas et al.,1995
Infrared Percentage Vegetation Index	IPVI	(NDVI+1)/2	Crippen et al., 1990
Normalized Difference Water Index	NDWI	$\frac{\rho 870 - \rho 1260}{\rho 870 + \rho 1260}$	González-Fernández et al., 2015

3.3.3. Pot culture experiment

Based on the results from the leaf rolling experiment, a pot culture experiment was also conducted. In this, based on the moisture absorbent growing media selected from the field were subjected to a pot culture experiment. These two different combinations of media and irrigation treatments (Field soil in combination with cocopeat (T1), Field soil alone (T2) with water stress and without water stress for both the combinations (T3) were taken as treatments. Thirty-day-old paddy seedlings were transplanted into pots and allowed to be established. These potted plants were irrigated for their successful establishment initially and later the water stress was introduced. One set of pots was maintained under flooded conditions and in the other set water stress was imposed by withholding the irrigation. In this experiment, the process of leaf rolling and how it was withdrawn by the plants, i.e. recovery to normalcy were also observed and video graphed using Sony Cybershot DSC - HX400V camera (Model No: 4958944 and Make: China) (Fig.3.17).

3.3.4. Statistical analysis

Statistical analysis such as t-test and two-actor ANOVA and post hoc (LSD) were accomplished using average values, and standard error using GRAPES software (Gopinath et al., 2021) and Pearson's correlation analysis was carried out using R software between yield and yield parameters and between spectral indices, RWC and ML Wherever the treatment differences were significant (t-test), the critical difference was worked out at a 5 per cent probability level. The non-significant treatment difference is denoted by NS.

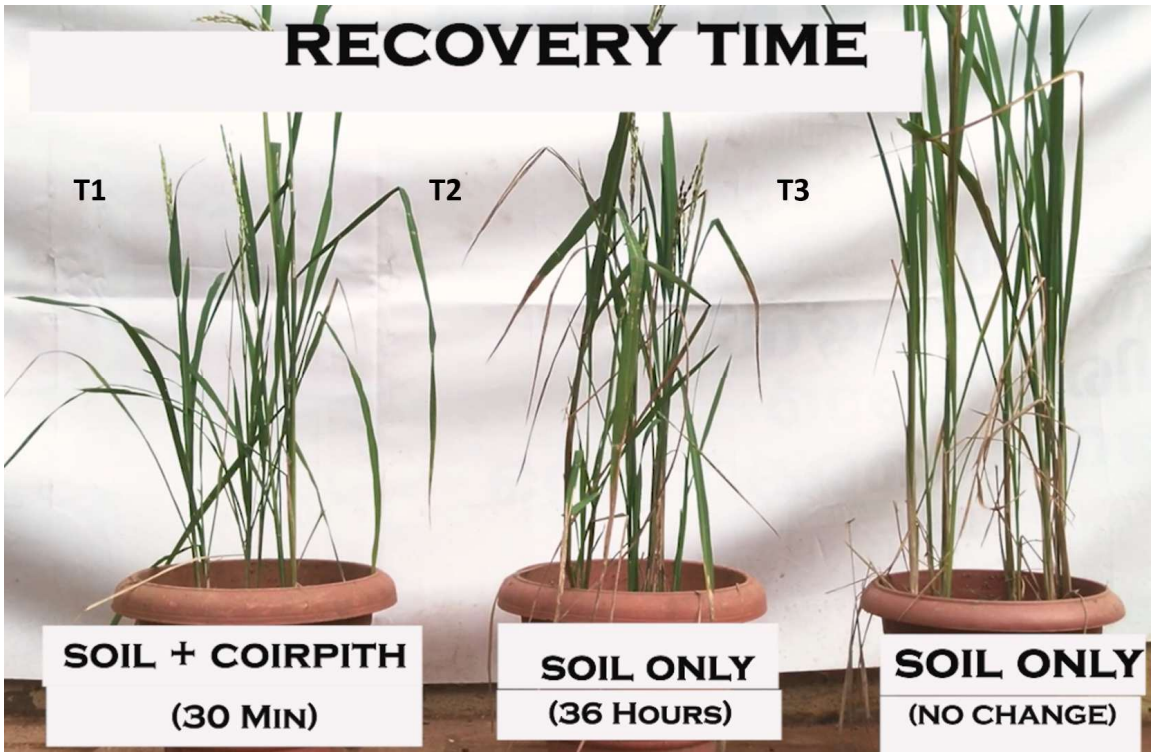


Fig.3.17. Screenshot from the experimental video showing the recovery time of different treatments

(T1- Field soil in combination with cocopeat in water stressed condition, T2- Field soil alone with water stressed condition and T3- Field soil alone without water stress)

3.4. Experiment – 4

Assessing the influence of different organic management practices on farmer's paddy yield

The fourth experiment was done in the farmers' field and was to assess the effect of different organic management practices and the detailed methodology for this experiment is being detailed hereunder.

3.4.1. Experimental layout

An experiment was conducted during the *Mudakan* season of 2020 on transplanted seedlings of rice with *Karuna* as the variety in the farmer's field at Peringalam, Kozhikode, Kerala. Twenty days- seedlings were transplanted in a farmer's field (Fig.3.18 & Fig.3.19). Five treatments were attempted which comprised different nutrient management practices *viz.,* P1- Application of basal nutrients only (FYMs); P2- Application of compost with basal nutrients and P3- Application of Azolla with basal nutrients, P4- Application of both compost and Azolla with basal nutrients, and C- Farmer's traditional management practices (Table 3.11). The recommended dose of fertilizers and FYMs were applied (KAU, 2016). All the cultural and management practices were adopted as per the package of practices of Kerala Agricultural University (KAU) combined with farmers' practices. Every regional custom and management approach was incorporated into the Kerala Agricultural University's (KAU) practice package. The P and K levels in organic manure were slightly adjusted to ensure that nitrogen application was consistent with the treatments. There were five treatments and four replications in the experiment. Irrigation requirement was monitored by canal irrigation in which the field was always maintained under flood conditions.

Fig.3.18. Data collection from the farmer's field

Table 3.11. Experiment 4 - treatment details

Treatments
P1- Application of basal nutrients only (FYMs)
P2- Application of compost with basal nutrients
P3- Application of Azolla with basal nutrients
P4- Application of both compost and Azolla with basal nutrients
C- Farmer's traditional management practices

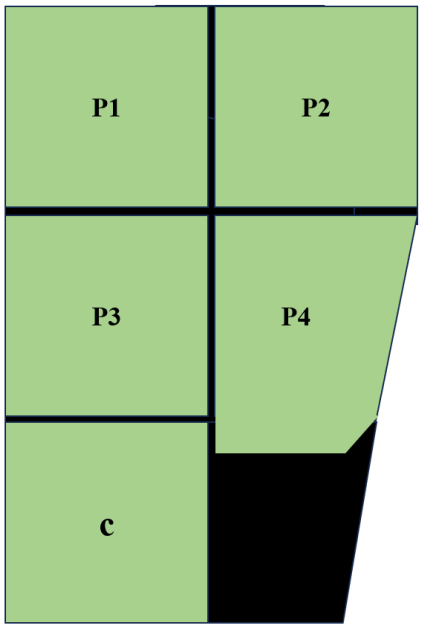


Fig.3.19. Experiment 4- diagrammatic representation of experimental field (P1- Application of basal nutrients only; P2- Application of compost with basal nutrients and P3- Application of Azolla with basal nutrients, P4- Application of both compost and Azolla with basal nutrients, and C- Farmer's traditional management practices)

3.4.2. Variety

Karuna (PTB 54) is a long-duration (140-145 days) rice variety that was selected for this experiment. It has a good yield response to low fertilizer regimes hence the cultivar is popular among Malabar farmers. The variety is known for its multiple resistance towards pets and is tolerant to metal iron toxicity. It is best suited to the second season.

3.4.3. Climatic parameters

Different climatic parameters namely, minimum temperature, maximum temperature, minimum relative humidity, rainfall, maximum relative humidity, solar radiation, and pan evaporation were measured throughout the crop period from the meteorological observatory of CWRDM.

3.4.4. Soil Characters

Soil samples were randomly gathered from experimental fields, encompassing two distinct depths: 0 to 15 cm and 15 cm to 30 cm. Subsequently, these samples underwent analysis to determine their physicochemical attributes, along with the available concentrations of nitrogen (N), phosphorus (P), and potassium (K), employing the methods outlined below. The collected samples were subjected to shade-drying, followed by pulverization and sieving through a 2 mm sieve. The resulting soil material was then analysed to quantify the levels of the specified available nutrients.

Soil physicochemical properties

3.4.4.1. Field capacity

Field capacity denotes the upper limit of water utilization by plants, offering optimal absorption of nutrients and water. The determination of field capacity involves employing a pressure plate apparatus, which applies a suction of -1/3 atmosphere to a saturated soil sample. A comprehensive procedure for this determination has been elaborated in section 3.1.4.1.

3.4.4.2. Permanent wilting point

The minimum amount of water in the soil that a plant needs to avoid wilting is known as the PWP. When a plant runs out of water, it reaches the permanent wilting point, which is typically at 15 bars. Even though there is still some water in the soil at this point, the roots are finding it challenging to draw it up. Detailed procedure is already explained section 3.1.4.1.

3.4.4.3. Soil pH

Soil pH was assessed using a 1:2.5 ratio soil water-suspension with the glass electrode (Jackson, 1973) using an Eutech pH & electrical conductivity meter (model number PC 510; serial number: 2237098).

3.4.4.4. Electrical Conductivity (EC)

Soil-water suspension of a 1:2.5 ratios was used for measuring electrical conductivity. It is measured with a Conductivity Bridge and expressed in dSm^{-1} (Jackson, 1973) using an Eutech pH & electrical conductivity meter (model number PC 510; serial number: 2237098).

3.4.4.5. Soil organic carbon

Soil organic carbon was determined through a chromic acid wet digestion method (Walkley & Black, 1934). Detailed procedure is already explained section 3.1.4.4.

3.4.4.6. Available nitrogen

The amount of soil available nitrogen in the soil sample was determined by alkaline permanganate method (Subbiah & Asija, 1956). Detailed procedure is already explained section 3.1.4.5.

3.4.4.7. Available phosphorous

The amount of available P from the soil was extracted with Bray I extractant (0.025 N HCl + 0.03 N NH_4F) blue colour was developed using ascorbic acid as reductant and the colour intensity was measured at 660 nm with a spectrophotometer (UV- Vis Spectrophotometer, model: Evolution 201, serial number: 5A4T146001) (Bray & Kurtz, 1945). Detailed procedure is already explained section 3.1.4.6.

3.4.4.8. Available potassium

Neutral normal ammonium acetate (N NH_4OAc) is used to extract the available potassium in the soil. The soil available potassium concentration was read in a flame photometer (Stanford & English, 1949). Detailed procedure is already explained section 3.1.4.7.

3.4.4.9. Available micronutrients

For determining the amount of accessible Zn, Cu, Mn, and Fe using an atomic absorption spectrophotometer, diethylenetriaminepentaacetic acid (DTPA) was utilized as an extractant.

Principle

DTPA forms stable complexes with Zn, Cu, Fe, and Mn. Its capacity to complex each of the micronutrient cations is 10 times its atomic weight.

Materials required

(i). DTPA 0.005 M, (ii). CaCl2 2H2O – 0.01M solution and (iii). Triethanolamine: 0.1 M solution.

The DTPA extractant solution was prepared by dissolving 13.3 ml of TEA, 1.967 of AR grade DTPA and 1.47 g of $CaCl_2$ in 100 ml of distilled water. The contents were allowed for some time so that the DTPA would dissolve and then diluted to about 900 ml. The pH of the solution was adjusted to 7.3 $\pm$ 0.05 with 1:1 HCl by stirring and the volume made up to 1 litre.

Preparation of standard solution

Zinc:

In a beaker, 5 ml of 1:5 H_2SO_4 was added after 0.439 g of AR grade $ZnSO_4.7H_2O$ had been dissolved in 200 ml of glass distilled water. The volume was made up when the contents were transferred to a one-litter volumetric flask. The result was 100 ppm of zinc. Working standards of 0, 0.1, 0.2, 0.4, and 0.6 g/ml (ppm) solutions were created from this stock solution.

Iron:

100 ppm of Fe solution was prepared when 0.702 g of AR grade ferrous ammonium sulphate was dissolved in 5 ml of 1:5 H_2SO_4 and built up to 1 litre. This stock solution was used to prepare working standard concentrations of 0, 1, 2, 4, and 6 ppm.

Manganese:

Potassium permanganate of AR grade weighed 0.288 g, and 300 ml of distilled water was used to dissolve it. This was mixed with 20 ml of concentrated H_2SO_4 and heated to 60 ^{0}C. Oxalic acid was then added drop by drop to the mixture to make it colourless. The mixture was cooled and built up to 1 litre, producing a stock solution with 100 ppm. Working standards of 0, 1, 2, 4, 6, and 8 ppm were created from the stock solution.

Copper:

100 ppm of copper was obtained from 0.392 g of AR grade $CuSO_4.5H_2O$ dissolved in glass distilled water and made up to 1 litre. Working standards for solutions at 0, 1, 2, 4, and 6 ppm were created from the stock solution.

For each nutrient, created a standard curve using the working standard solutions. Plotted the values of absorbance against concentrations and estimated the nutrient concentration mentioned below:

* 10 g of the soil sample, which had been air dried, was placed in a 150 ml conical flask with 20 ml of the DTPA extractant solution and shaken for 2 hours in a horizontal shaker.
* Filtered through Whatman no.40 filter paper.
* Calculate the concentration of each micronutrient in the sample using the standard curve and the measurement of the filtrate from the atomic absorption spectrophotometer.

Critical levels: Zn 1.2 ppm, Cu 0.72 ppm, Fe 3.7 ppm (non-calcareous soil) 6.3 ppm (calcareous soil) Mn 2.0 ppm.

3.4.4.10. Available boron

Principle

Boron is extracted using hot water and then treated with azomethine-H, which joins with boron to create a stable complex at a pH of 5.1.

Materials required

(i). Buffer solution: 250 g of ammonium acetate and 15 g of EDTA disodium salt dissolved in 400 ml of water to which 125 ml of glacial acetic acid was added, (ii). Azomethine - H reagent: 0.45 g of azomethine- H dissolved in 100 ml of 1 % L-ascorbic acid (prepared afresh) (iii). Conical flask 250 ml, (iv.) Volumetric flask 25 ml and (v). Spectrophotometer.

Standard boron solution

0.570 g of AR grade boric acid (H_3BO_3) dissolved in 1 litre of distilled water to 100 ppm boron solution. From this stock solution prepared working standards of 0, 0.05, 0.1, 0.2, 0.4, 0.6, and 0.8 ppm solutions by dilution.

2 ml of a series of standard solutions were transferred to 25 ml volumetric flasks. Added 2 ml of the Azomethine-H reagent solution and 2 ml of the buffer solution. Then vigorously shook and let stand at room temperature for 30 minutes. Fill the container with water, then use a spectrophotometer to measure the amount of colour generated at 430 nm.

Take an absorbance reading for a range of concentrations between 0 and 1 ppm. Plot the concentrations versus absorbance on a semi-log paper to create a standard curve.

Estimation of boron in soil sample

- 25 g soil sample, 50 ml of water, and 0.5 g of activated charcoal were transferred to a conical flask. 5 minutes of boiling followed by an immediate filtering via No. 42 filter paper.
- Pipetted out 5 ml of the filtrate to a 25 ml volumetric flask and added 4 ml of buffer and 4 ml of Azomethine - H reagent and allowed it to stand for 1 hour for colour development and make up the volume.
- Calculate the boron content by measuring the colour intensity with a spectrophotometer at 430 nm and using the standard curve as a guide

3.4.4.11. Calcium and Magnesium

Principle

The Versenate technique was used to estimate calcium and magnesium. Magnesium (Mg) and Calcium (Ca) are complexed by EDTA in the following order: Mg first, then Ca. Ca is first calculated using a Murexide indicator at pH 12 with sodium hydroxide present. Then, Ca + Mg are calculated using Eriochrome black-T at pH 10 with a buffer solution containing ammonium hydroxide and chloride of ammonium.

Materials required

(i). 0.02N EDTA, (ii).10 % sodium hydroxide, (iii). Ammonium chloride - ammonium hydroxide buffer solution, (iv). Murexide indicator, (v). Eriocohrome Black-T indicator, (vi)Litmus paper, (vii). Porcelain basin, (viii). Burette and (ix). Pipette.

Procedure

- 10 ml of sesquioxide filtrate was poured into a porcelain bowl.
- Drop by drop, added ammonium chloride-ammonium hydroxide butter solution to balance the acidity, then added an extra 5 ml to keep the pH at 10.
- A few drops of the Eriochrome black-T indicator solution were then added, and the colour was titrated with 0.02N EDTA until it turned sky blue.

Calculation

Weight of soil sample taken = W g

Volume of HCl acid extract prepared = 500 ml

Volume of HCI acid extract pipette out for

R_2O_3 estimation = 50 ml

Volume of R_2O_3 filtrate made up to = 250 ml

Volume of R_2O_3 filtrate pipette out for

calcium estimation = 10 ml

Volume of 0.02N EDTA used for Ca + Mg = a ml

Volume of 0.02N EDTA used for Ca alone = b ml

Volume of 0.02N EDTA used for Mg alone = (a-b) ml

1 ml of 0.02N EDTA = 0.0004 g Ca or 0.00024 g Mg

% of Ca on moisture free basis $= 0.0004 \times b \times \frac{250}{10} \times \frac{500}{50} \times \frac{100}{W} \times \frac{100}{(100-M)}$

% of Mg on moisture free basis $= 0.00024 \times (a-b) \times \frac{250}{10} \times \frac{500}{50} \times \frac{100}{W} \times \frac{100}{(100-M)}$

(M = Moisture percentage of the soil)

3.4.5. Observations

Field observations were taken in the four different growth stages of the crop. In order to take the observations five plants have been selected randomly from each plot avoiding the border plants at different developmental stages of rice, i.e., tillering (30th day), flowering (60th day), maturity (85th day) and harvest (110th day) were tagged. Biometric, physiological and yield parameters of these plants were observed.

Biometric characters

3.4.5.1. Plant height

Plant height at regular intervals was noted using a meter scale in centimetres. The height of the plants from the base/ above the ground level to the tip of the longest leaf has been recorded for all five observational plants in each plot.

3.4.5.2. Number of tillers

Total number of tillers was counted from the base and expressed as numbers.

3.4.5.3. Leaf area index

The leaf area of the flag-leaf was found out by direct method using the given formula by measuring the length and maximum width (middle portion) of the flag leaf. Also measured by the graphical method by sketching the outline of the leaf on graph paper and calculated its area.

$$\text{LAI} = \frac{\text{L} \times \text{W} \times \text{K} \times \text{No. of leaves plant}^{-1}}{\text{Land area occupied by plant}}$$

Where, L - Length of leaf (cm)

K - Correction factor (0.75)

W - Width of leaf (cm).

3.4.5.4. Number of panicles

The number of panicles per plant was counted.

3.4.5.5. Root length

Each plot had five hills, which were meticulously removed without significant root damage. The root length of each plant was quantified by measuring from the base to the tip of the longest root and reporting the measurement in centimetres.

3.4.5.6. Yield

At the harvest grain yield of each plot has been recorded in kg ha $^{-1}$.

3.4.6. Statistical analysis

A one-way ANOVA (analysis of variance) was conducted and the significant difference level was expressed at the $p < 0.01$ and 0.05 probability levels and non-

significant treatments are denoted as NS (Gopinath et al., 2021). Pearson's correlation analysis was carried out using R software between yield and soil characters.

3.5. Experiment -5

Assessing the effect of different water and straw management practices on decomposition and GHG emission in post-harvest rice fields

The next experiment was conducted at the IRTA experimental station (40°42′27.5" N 0°37′59.8″E) in the Ebro Delta, Spain as a part of **CLIFF-GRADS scholarship programme** (The Climate, Food and Farming, Global Research Alliance Development Scholarships Programme is a joint initiative of the **CGIAR** Research Program on Climate Change (**CCAFS**) low emissions development flagship and Global Research Alliance (**GRA**) on Agricultural Greenhouse Gases and Mitigate+: Research for Low Emissions Food Systems (Mitigate+). The experiment was conducted to assess the different post-harvest field management to lower greenhouse gas (GHG) emissions. The field experiment was started in post-harvest 2017 and has been running for 5 years, up to post-harvest in 2022. The data collection was comprised of the post-harvest seasons of 2022 and the pre-growing season of 2023 (Table 3.12).

Table 3.12. Experiment 5- Details regarding the experimental period and rice cultivation cycle

Seasons	**Time period**	**Water condition in WFL**	**Water condition in NFL**
Pre-growing 2022	Jan – Apr 2022	Dry	Dry
Post-harvest 2022	Oct– Dec 2022	Flooded	Dry
Treatment			
Water management		**Timing of straw incorporation**	
WFL- Winter flooding		ESI - Early straw incorporation	
NWF - non-winter flooding		LSI – Late straw incorporation	

3.5.1 Design and Layout

The experimental design was a split-plot two-factor design with three replicates, where the main plots represented the water management and the subplots represented the timing of straw incorporation management during post-harvest seasons i.e., winter flooding (WFL) vs non-winter flooding (NWF) and early (ESI) vs late (LSI) straw incorporation. WFL-ESI is representative of the conventional post-harvest management practice in Ebro Delta rice fields. The experiment was laid out in two adjacent experimental fields of 106×10 m each (subplots: 53×10 m) (Fig. 3.20). Every plot had its own water input, allowing for autonomous irrigation management. The experimental plots were cultivated following the standard management of the rice-growing area (Belenguer-Manzanedo et al., 2022).

Irrigation was done with the help of the irrigation community in Ebro Delta, Catalonia. During the growing season, paddy fields were flooded (deep of water layer, 7-10 cm deep) until 2 weeks before harvest and managed similarly irrespective of the post-harvest treatments following the standard management practices of the region in the Ebro delta. Soil water level and temperature were continuously monitored throughout the experimental period.

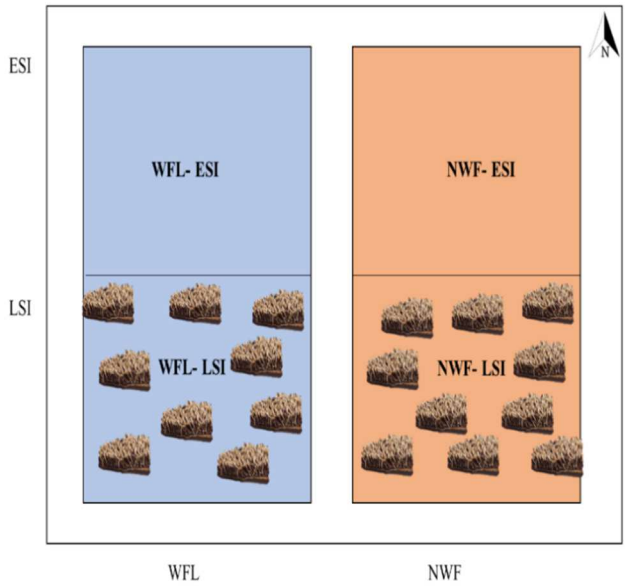


Fig.3.20. Experiment 5- diagrammatic representation of experimental plot (NWF ESI- Non winter flooding with early straw incorporation; NWF LSI- Non winter flooding with late straw incorporation; WFL ESI- Winter flooding with early straw incorporation; WFL LSI- Winter flooding with late straw incorporation)

In post-harvest management, NWF plots, the fields were allowed to naturally drain after the harvest by drainage channels, constructed in between the two main plots to avoid water seepage from the flooded field. In ESI plots, straw was incorporated into soil by mechanically ploughing in November month (04/11/2022). Whereas in LSI, the straw was mixed in late December (14/12/2022).

3.5.2 Straw/ litter/ mesh bag experiment

Fig.3.21. Coarse and find litterbags in the flooded post-harvest paddy field of late straw incorporation management field

To investigate the difference in straw decomposition in experimental fields, rice straw/ litter bags were incorporated into the soil. The straw used in this study was obtained from the previous growing season after harvest. Each litter bag comprised of 10g of small (5-7 cm) straw pieces evenly distributed in 15 cm x 20 cm bags of two mesh sizes: (fine, 20 µm x 20 µm and coarse, 5 mm x 5 mm). A total of 12 pairs (1 fine & 1 coarse) of straw bags were prepared, and 3 pairs were buried into the soil, at 5 cm -10 cm depth and 10 cm apart from each other, at three random points in each treatment (Fig.3.21).

Rates of straw decomposition were assessed in the 2022 post-harvest season while loss of straw weight in both post-harvest seasons in 2022 and in the 2022 growing season.

3.5.2.1. Assessment of mass loss

In ESI management fields, straw bags were buried on the 4th of November of 2022 in the post-harvest period. Whereas in LSI fields, straw bags were left on the aboveground of the fields to simulate the natural conditions of straw and on 14th December 2022, they were buried inside the soil and retrieved after 116 days. In the growing season of 2022, straw bags were buried in the four different management fields before seeds sowing (in June 2022) and retrieved them after 120 days of incorporation, just before harvest.

Retrieved straw bags were shade-dried and cleaned without disturbing the straw inside. Then straw from the bags was taken out and kept for drying in the oven at 60 ^{0}C for 3 days (Schmidt et al., 2016a) and measured the remaining weight and calculated the percentage mass loss from each bag.

$$Percentage\ mass\ loss\ (\%) = \frac{Initial\ weight - Final\ weight}{Inital\ weight} x100$$

3.5.2.2. Assessment of straw decomposition rates

To determine the decomposition rates of each treatment, we have conducted a series of litter bag experiments with different extraction times. This was conducted during the post-harvest season of 2022. There was total five different extractions (E1, E2, E3, E4, & E5) from each treatment for both coarse and fine mesh bags with nine replications. In early straw incorporation (ESI) management, all the litter bags were buried on the same day (on 6th October 2022) and retrieved after 5, 10, 25, 60 and 138 days. In late straw incorporation (LSI) management, all the litter bags were kept on the surface of the paddy field on the same day as in ESI and buried inside the soil after 55 days (30th November 2022), coinciding with the straw input operation in the field. Thereafter, litter bags were retrieved after 4, 11, 19 and 83 days after burial.

Retrieved straw bags were shade-dried and cleaned. After cleaning straw from the bags was taken out and kept for drying in the oven at 60 ^{0}C for 3 days (Schmidt et al., 2016b) and measured the remaining weight and plotted against the time period also estimated the decomposition rate constant *k,* as an exponential function of remaining weight decomposition curve (Keuskamp et al., 2013).

$$y = a^{-kt} + b$$

3.5.3. Greenhouse gas sampling

In the present experiment, GHG sampling from the post-harvest season of October 2022 – February 2023 was monitored. Using the lightweight transparent chamber and the sampling technique proposed by Altor & Mitsch (2008), greenhouse gas emissions were measured. A square-based polyvinyl chloride (PVC) chamber with dimensions of 0.35 m width, 0.35 m breadth, and 0.74m height and a volume of 0.093 m^3 made up the chambers (Fig.3.22). To prevent gas exchange while samples were being taken, rubber septa were used to seal two openings for thermometer and syringe insertion. Foams were used to cover the chamber's foundation, allowing it to be placed without disturbing the paddy fields. In

the non-flooded condition (dry), the foam was removed, and chambers were gently covered on the ground with moist towels without any opening at the base to prevent gas exchange with its atmosphere. Throughout the whole study period, measurements were taken weekly per triplicate in each treatment.

Fig. 3.22. Greenhouse gas sampling chambers in post-harvest paddy fields (left - non flooding management field and right - flooding management field)

The syringe was flushed initially to mix headspace air before gas samples were taken. A 30 ml sample of gas was then collected and transferred over pressured to glass vacuum 12.5 ml vials (Labco Ltd., Buckinghamshire, UK). For each replication, gas samples were taken four times, once every ten minutes, as To, T1, T2, and T3. With each sample of a gas, the chamber's air temperature was recorded. Utilizing a gas chromatograph, the Agilent 8860 GC System (Agilent USA) measured the concentration of CH_4 gas (Belenguer-Manzanedo et al., 2022).

A linear regression between gas concentration and time was used to calculate gas emission rates. Since the pressure was maintained constant through a tube connecting the headspace to the outside, the ideal gas law was used to adjust each sample's gas concentration for the rise in temperature in the chamber's headspace. According to Martnez-Eixarch et al. (2018, 2021), only significant linear regressions (P0.05 and R^2 >0.80) were accepted to reflect changes in gas emission, and non-significant regressions were used to represent zero emission rates.

3.5.4. Statistical analysis

Statistical analysis (a two-way ANOVA) was conducted using R software. Tukey's Honest Significant Different (HSD) post-hoc test (P <0.05) was conducted to identify the statistically significant treatments.

3.6. Experiment -6

Calibration and validation of crop simulation model -DSSAT and temperature sensitivity analysis

This experiment was conducted to understand the application of the crop simulation model, DSSAT, for water and nutrient management on the yield of rice under different climatic scenarios and to understand the impact of temperature on rice yield with sensitivity analysis using DSSAT model. The results of this study are detailed hereunder.

3.6.1. DSSAT- CERES-Rice model

DSSAT- CERES (Crop Estimation through Resource and Environment Synthesis) model is a Windows-based crop simulation model (DSSAT version 4.0) (Fig.3.23.) An input-output data-sharing format-compatible set of crop simulation models has been created and integrated into a computational software program known as the DSSAT (Decision Support System for Agro-technology Transfer) Model. CERES- Rice model can be used in a wide range of research problems like the effect of irrigation, nitrogen, the impact of environmental conditions, yield gap analysis, the effect of climate change on rice production. Above all, the major objective of this model is to support farmers by recognizing the problems which limit yield and to study thrust areas which improve the cropping system. In this experiment, we give the input data including weather data, soil data and crop management data. This experiment mainly focuses on the impact of method of planting and nutrient management on rice production in Kerala.

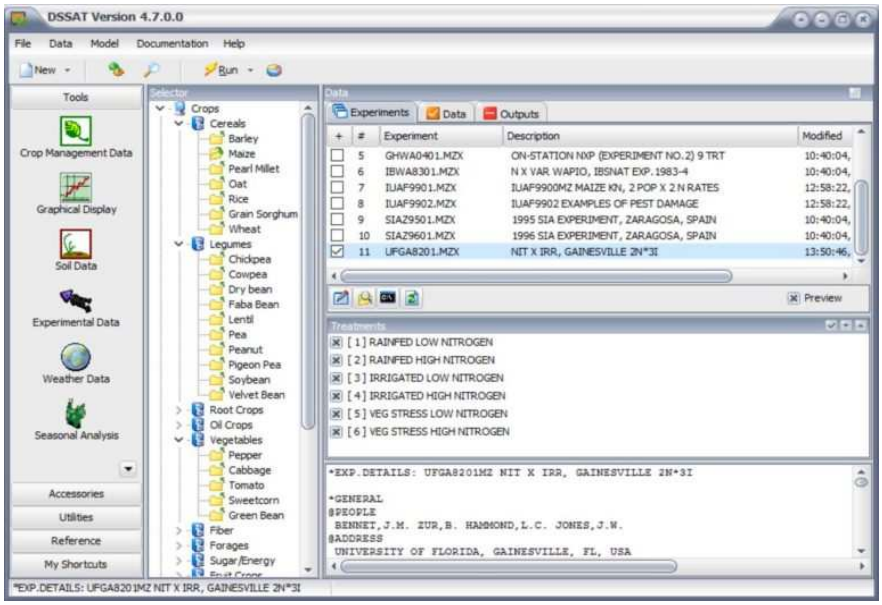


Fig.3.23. Home page of DSSAT CERES-Rice model software

3.6.1.1. Input files and experiment data files

Input files and experiment data files required to run the CERES-Rice model are given in Table 3.13.

Table 3.13. Input files of DSSAT- CERES-Rice model

Internal file name		Description	Name
Experiment	FILEX	Experiment details file for a specific study. Encompassed within are data sets pertaining to various aspects, including treatment variables, field conditions, crop management parameters, and controls utilized for simulation.	CWRDM19.RIX
Weather and soil	FILEW	Meteorological data recorded daily at CWRDM station over a year and is included in the dataset.	CWRDM20.WTH
	FILES	The dataset contains soil profile data obtained from a set of experimental sites, specific to a particular institute.	SOIL.SOL
Crop and cultivar	FILEC	The dataset includes cultivar/variety coefficients tailored for a specific crop species, such as rice, within the framework of the 'CERES' model, version 046.	RICER047.CUL[1]
	FILEE	The dataset comprises ecotype-specific coefficients designed for a particular crop species, like rice, within the context of the 'CERES' model, version 046.	RICER046.ECO[1]
	FILEG	The dataset includes crop-specific coefficients tailored for a particular model, such as rice coefficients for the 'CERES' model, version 046.	RICERO46.SPE[1]
Experiment data files	FILEA	The dataset comprises average values of performance data derived from a rice experiment. These values are intended for comparison with summary results generated by a model.	CWRDM20.RIA
	FILET	The dataset encompasses time-course data, presented as averages, derived from a rice experiment. These data are employed for graphical comparisons between measured and simulated time-course results.	CWRDM20.RIX

These names adhere to a standardized naming convention, where the initial two spaces are designated for the crop code, the subsequent three characters represent the model's name, and the final three characters signify the model version.

3.6.1.1.1. General information

Basic data about the experiment and experimental site are needed for the successful running of the model, which is presented in Table 3.14 (Fig.3.23).

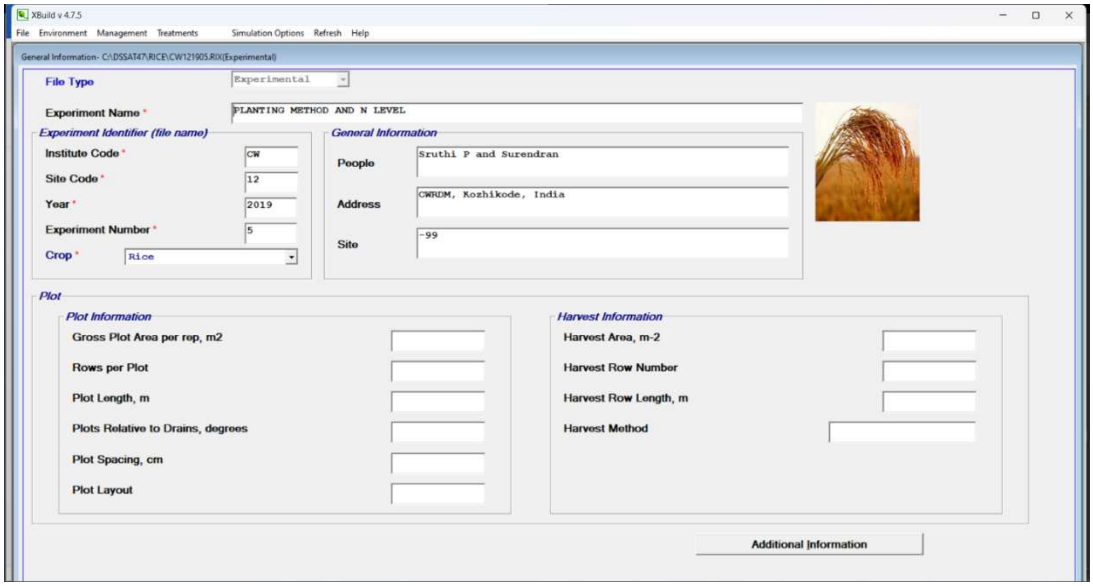


Fig.3.24. DSSAT screen showing general information regarding the experiment

Table 3.14. General information of the experiment in DSSAT software

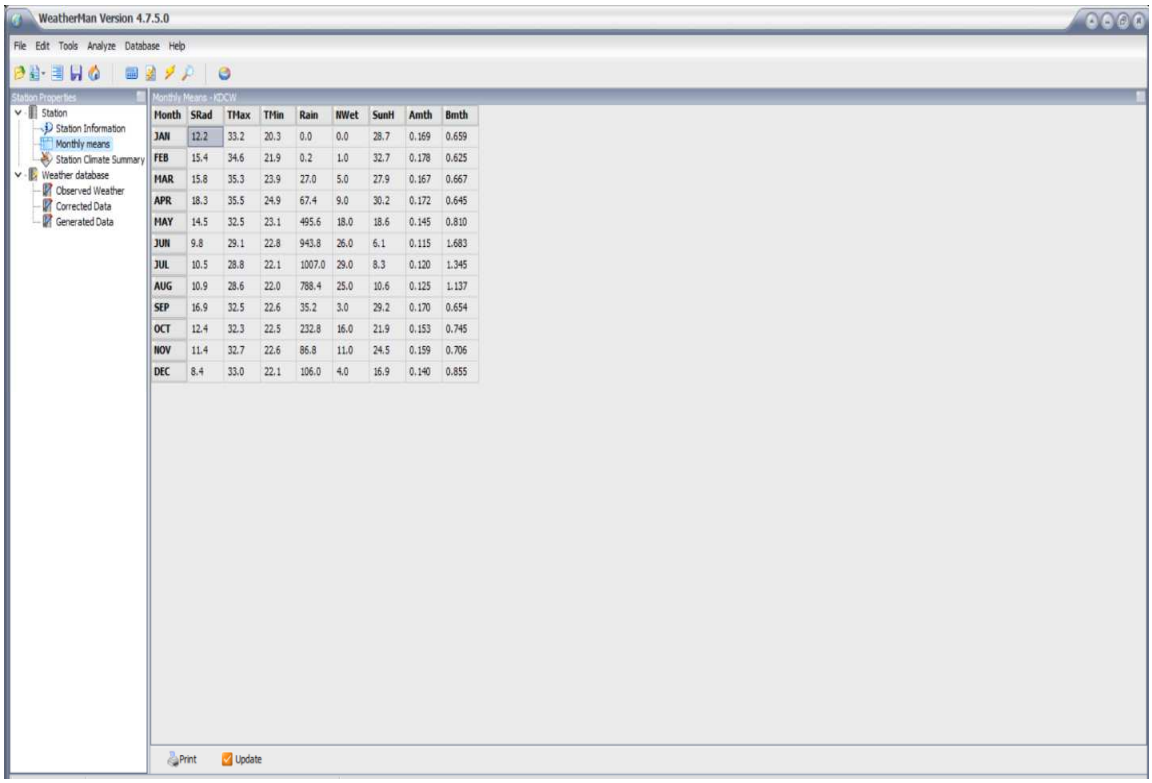
Variable	Input
Experiment name	Assessment of method of planting and nutrient level
Institute code	CW
Site code	12
Year	2019
Experimental number	5
Crop	Rice
People	Sruthi P, Dr U Surendran
Address	Kunnamangalam, Kozhikode, Kerala, India
Site	CWRDM

3.6.1.1.2 Weather file

Latitude, longitude, geological location, elevation from the sea level and climatic conditions of the experimental area are required to create the weather file. Date (Year Day-of-Year Format (yyddd)), maximum temperature (T max in ^{o}C), minimum temperature (T min in ^{o}C), rainfall (mm), Relative humidity (RH), wind speed (m/s), Total daily sunshine hours (hrs), and SPARD (Total daily solar radiation in MJ/M^2/d) of the experimental site for the crop duration was recorded and uploaded in as weather file in the weatherman tool of DSSAT software as monthly mean data of the above-mentioned inputs (Fig.3.25).

3.6.1.1.3. Soil file

S Build, which generates a soil file, was used to produce the soil profile. The soil samples of the experimental site were collected from the field, and they underwent physical and chemical analysis in the lab. These data were entered into the software after creating the soil profile. To run the CERES-Rice model, this data is used to create the soil file (SOIL.SOL).



Month	SRad	TMax	TMin	Rain	NWet	SunH	Amth	Bmth
JAN	12.2	33.2	20.3	0.0	0.0	28.7	0.169	0.659
FEB	15.4	34.6	21.9	0.2	1.0	32.7	0.178	0.625
MAR	15.8	35.3	23.9	27.0	5.0	27.9	0.167	0.667
APR	18.3	35.5	24.9	67.4	9.0	30.2	0.172	0.645
MAY	14.5	32.5	23.1	495.6	18.0	18.6	0.145	0.810
JUN	9.8	29.1	22.8	943.8	26.0	6.1	0.115	1.683
JUL	10.5	28.8	22.1	1007.0	29.0	8.3	0.120	1.345
AUG	10.9	28.6	22.0	788.4	25.0	10.6	0.125	1.137
SEP	16.9	32.5	22.6	35.2	3.0	29.2	0.170	0.654
OCT	12.4	32.3	22.5	232.8	16.0	21.9	0.153	0.745
NOV	11.4	32.7	22.6	86.8	11.0	24.5	0.159	0.706
DEC	8.4	33.0	22.1	106.0	4.0	16.9	0.140	0.855

Fig.3.25. Monthly mean data of Weather file generated in Weather Man Module of DSSAT

3.6.1.1.4. Crop management file

All the crop-related inputs for the model's simulation are contained in this file. It contains all information regarding the primary conditions and characteristics of the experimental field, including the experiment name, site code, year of conduct, participants, address, plot size, plot spacing, plot layout, harvest area, method, weather station details, field ID, drainage type, soil name, surface texture, depth, irrigation, and water management details, inorganic nitrogen conditions, planting details, fertilizer details, chemical application, and organic fertilizer.

3.6.1.1.5. Cultivar

For this investigation, the Uma cultivar of rice was chosen from among the many cultivars.

3.6.1.1.6. Planting

In the planting data window of model requires details regarding the following: planting date DD/MM/YYYY), emergence date, (DD/MM/YYYY), planting method, plant population at seeding (plants, m^{-2}), planting distribution, plants population at emergence (plants, m^{-2}), row spacing (in cm), row direction (degree from North) and planting depth (in cm) (Fig.3.26).

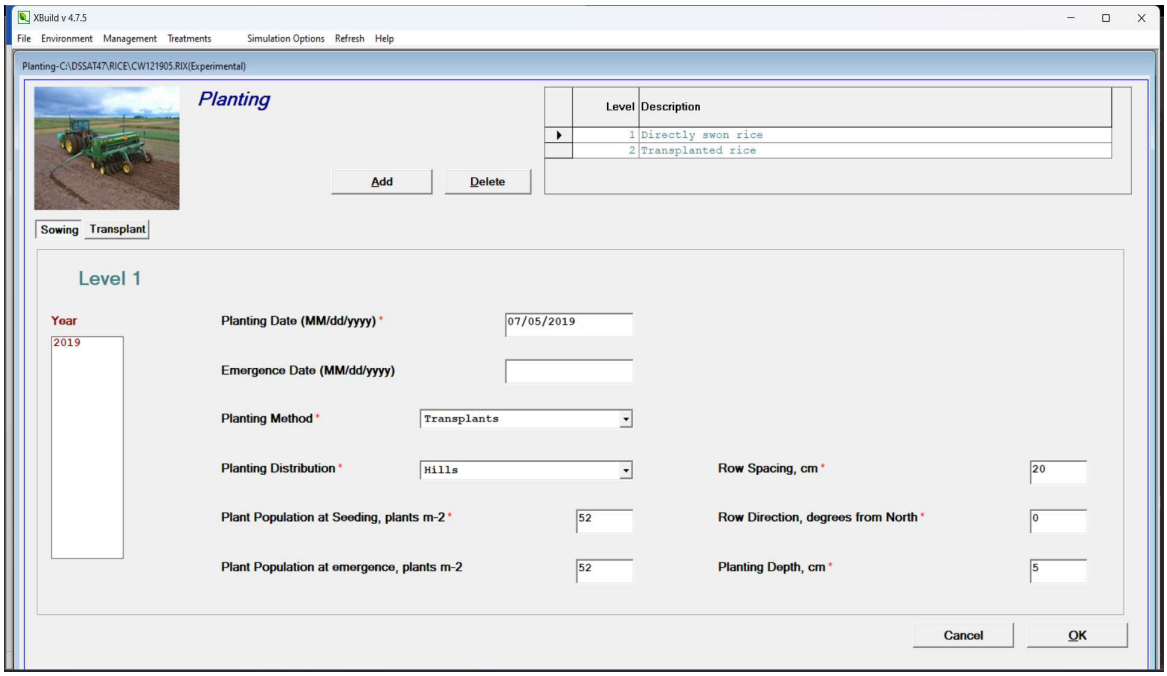


Fig.3.26. DSSAT window showing planting details

3.6.1.1.7. Irrigation

This window of the DSSAT models required the management details about different irrigation treatments as level 1, level 2, and so on depending on the number of irrigation treatments. It also required daily data on the amount of irrigated water with the mode of irrigation.

3.6.1.1.8. Fertilizer

This window of the DSSAT models (Fig.3.27) required the management details about different nutrient (N) treatments as level 1, level 2, and so on depending on the number of treatments with the quantity of nutrients supplied with each fertilizer application (N, P, K, and Ca) in kg ha^{-1}.

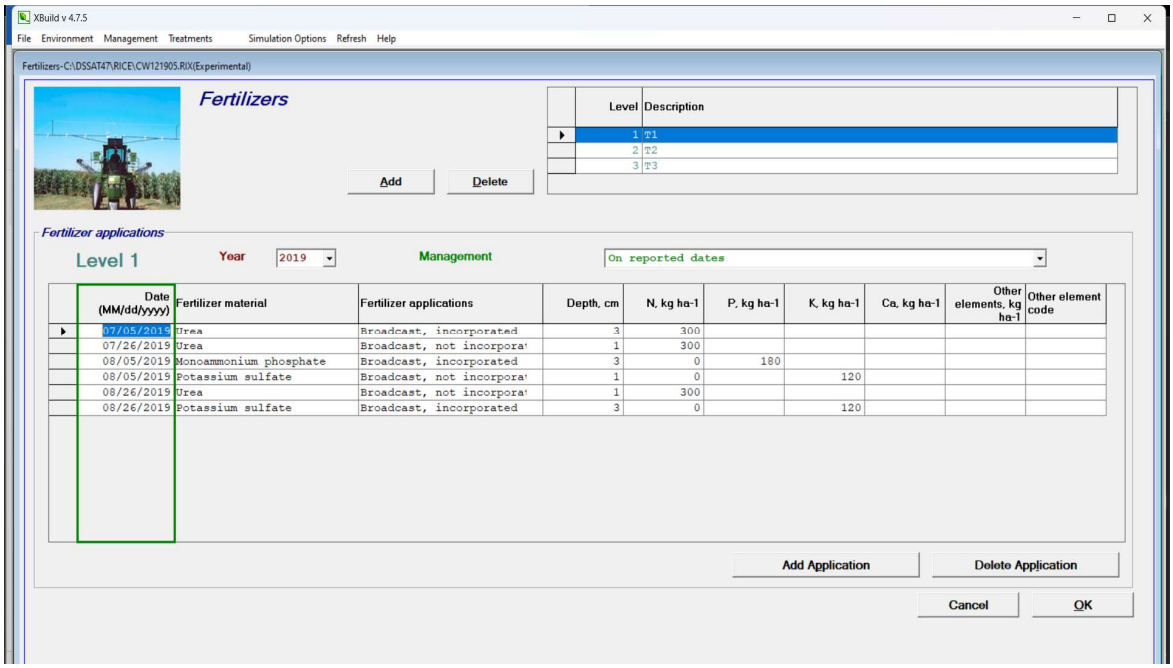


Fig.3.27. DSSAT window showing fertilizer application details

3.6.1.1.9. Treatment

This window of the DSSAT models carries the summary matrix of the different water and nutrient managements adopted for this experiment (Fig.3.28).

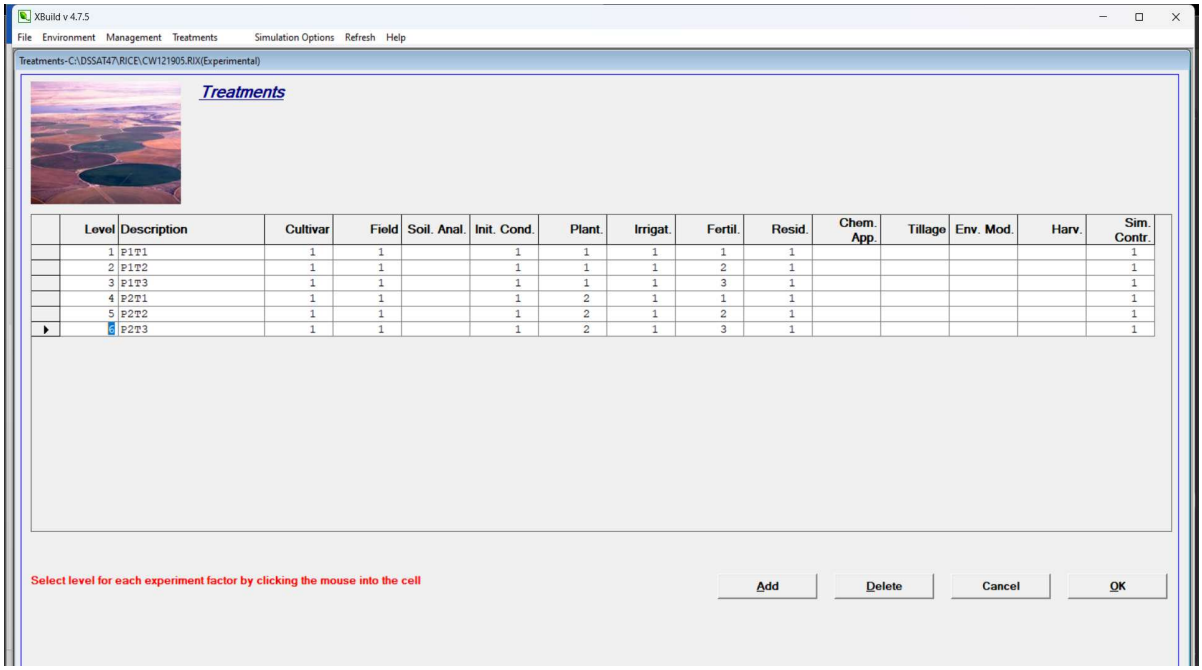


Fig.3.28. DSSAT window showing treatments details

3.6.1.1.10. Simulation options

This window of the DSSAT models carries different simulation options with respect to management, methods, and output regarding the prediction of yield for the experiment (Fig.3.29).

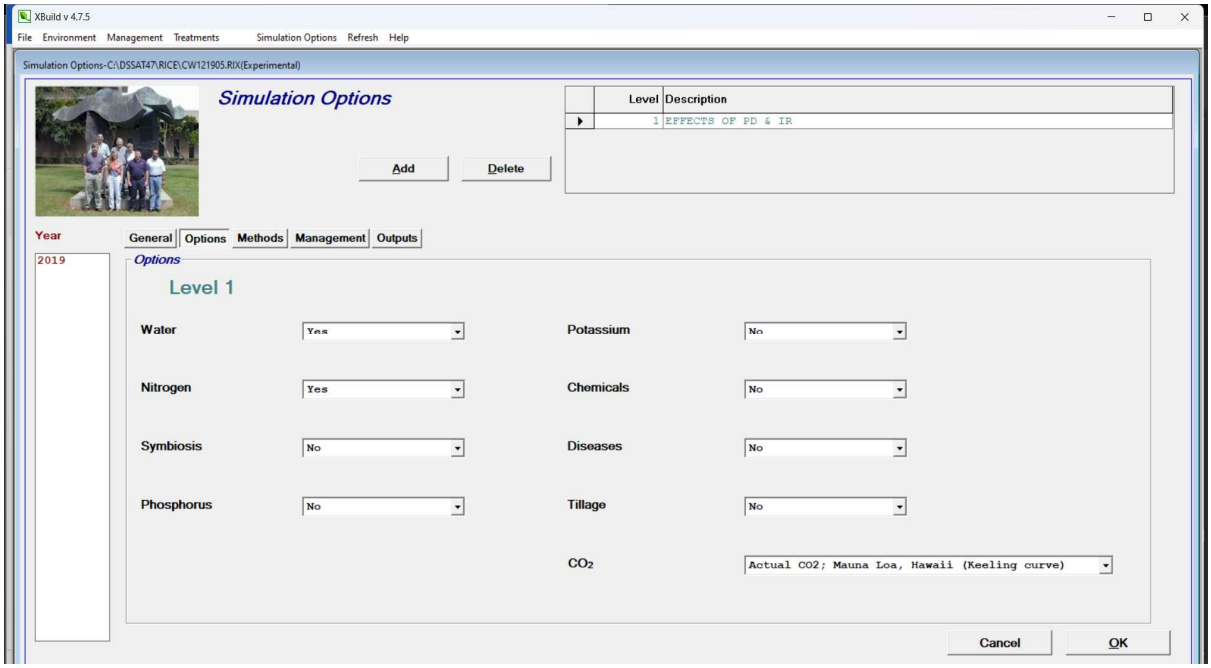


Fig.3.29. DSSAT window showing simulation options details

3.6.1.1.11. Genetic coefficients

The calibration method made use of data from the experimental field for the 2019–2020 experimental year. Genetic coefficients are adjusted via model parameterization and calibration, and simulated results are then contrasted with actual values. The DSSAT-CERES-Rice model's developmental stages, which were derived irrelatively, are caused by genetic coefficients.

3.6.1.1.12. GENCALC

The Decision Support System for Agrotechnology Transfer (DSSAT) interface's Genetic Coefficient Calculator (GENCALC), a software program, was used to estimate the genetic coefficients for the rice cultivar for crop growth and then to calibrate the CERES-Rice model. There are eight different coefficients available for rice cultivars (Table 3.15).

Table 3.15. Genetic coefficients available for rice cultivar

Coefficients	Explanations
P1	Time from seed emergence to the end of juvenile phase (expressed as growing degree days (GDD) in ◦C).
P2O	Critical photoperiod or the longest day length (in hours)
P2R	extent to which phasic development leading to panicle initiation is delayed (GDD in ◦C)
P5	time period from grain filling to physical maturity (GDD in ◦C)
G1	Maximum spikelet number coefficient
G2	Maximum possible single grain weight (g) under ideal growing conditions
G3	Scalar vegetative growth coefficient for tillering relative to the IR64 tillering coefficient.
G4	Temperature tolerance is the scalar coefficient

3.6.1.2. Output files

After all the anticipated files were created, the model was then run for all the treatments. Output files given by the models which are useful for the users are given in Table 3.16.

Table 3.16. Output files of DSSAT-CERES-Rice model

Internal file name	Description	File name
OUTO	Overview of inputs and major crop and soil variables.	OVERVIEW.OUT
OUTS	Summary information: crop and soil input and output variables; one line for each crop cycle or model run.	SUMMARY.OUT
SEVAL	Evaluation output file (simulated vs. observed).	EVALUATE.OUT
OUTWTH	Daily weather	Weather. OUT
OUTM	Daily management operations output file.	MgmtOps. OUT
ERRORO	Error messages	ERROR.OUT
OUTINFO	Information output file	INFO.OUT
OUTWARN	Warning messages	WARNING.OUT

3.6.1.3. Model calibration and evaluation

Calibration is the process of making arbitrary changes to parameter/ coefficient values in a model to match data from the real experiment. This is done by adjusting the genetic coefficients. Calibration of genetic coefficient CERES-Rice model has been done with the maximum available data. Common tools of statistics like Root Mean Squared Error (RMSE), Normalized Root Mean Square Error (nRMSE), Mean Bias Error (MBE),

correlation coefficient (r^2), and index of agreement (D-stat or D- index) are used to evaluate the goodness of fit and performance of the model.

The difference between the observed yield from the field experiment and the simulated yield from the DSSAT model was compared using the RMSE. RMSE should be close to 0 to provide the best match between observed and simulated data.

$$RMSE = \left[N^{-1}\sum_{i=1}^{n}(p_i - o_i)^2\right]^{0.5}$$

Where, p_i = simulated value

o_i =observed value

N = number of observations

The normalized root mean squared error is referred to as the nRMSE. It is a statistical indicator of a model's fit to the data that has been observed. Depending on the information and the goal, there are various methods for calculating the nRMSE.

$$nRMSE = \frac{\text{RMSE}}{Omax - Omin}$$

Where, *O max* -Maximum observed value

O min - Minimum observed value

A statistical measure of the average difference between a variable's observed and anticipated values is called mean bias error, or MBE. It is employed to calculate the model's or estimating method's bias or systematic error. Whereas a negative MBE suggests that predictions are less than the observations, a positive MBE shows that the predictions are greater. When the MBE is 0, there is no bias in the forecasts.

$$MBE = \frac{1}{n} + \sum_{i=1}^{n}(Pi - Oi)$$

Where, p_i = simulated value

o_i =observed value

n = number of observations

One metric used to assess a model's forecasting performance is the mean absolute percentage error or MAPE. The percentage error, which is the ratio of the difference between the

actual and predicted values to the actual value, is computed by averaging the absolute percentage errors of each data point.

$$MAPE = \frac{1}{n} + \sum_{i=1}^{n} \left| \frac{Oi - Pi}{Oi} \right| x$$

Where, p_i = simulated value

o_i =observed value

n = number of observations

The regression model's best data fit is determined by the r^2 correlation. The value of r^2 ranges from 0 (worse condition) to 1 (best fit condition).

$$r^2 = 1 - \frac{\sum(o_i - p_i)^2}{\sum(o_i - \bar{o})^2}$$

Where, o_i= i th observation of parameter o,

p_i= i th simulation of a parameter of p and

$\bar{o}$ = arithmetic means of parameter o.

The model's simulated outputs were assessed based on the variable's observed outputs using the D-index, a unitless measure of fit. A D-index value near 1.0 indicates that the observed and simulated data are perfectly fitted. The D-index was employed to test for under- or overestimation of the model.

$$D - index = 1 - \left[\sum_{i=1}^{n} (p_i - o_i)^2 / \sum_{i=1}^{n} (|p_i'| + |o_i'|)^2 \right]$$

Where $p_i' = p_i - \bar{o}$

$o_i' = o_i - \bar{o}$

The comparison of simulated and observed values from all twelve treatments is used to assess the performance of the DSSAT model.

This model simulates a range of processes, including the phenological development of the crop, growth of leaves, stems, and roots, biomass accumulation, and partitioning among leaves, stem, panicle, grains, and roots. Additionally, it accounts for soil water balance, water use by the crop, and soil nitrogen transformations along with nitrogen uptake by the crop. The phenological stages simulated by the model encompass sowing or

transplanting, germination, emergence, juvenile phase, panicle initiation, heading, beginning of grain filling, end of grain filling, and physiological maturity. The total biomass of the crop is simulated by multiplying the growth duration with the average growth rate. Furthermore, the model predicts yields by simulating these fundamental processes at the process level (Singh et al., 2022a).

Then the model was employed to simulate the grain yield of the *Uma* variety at their ideal nitrogen and irrigation requirement for the Kozhikode district.

3.6.1.4. Model simulation under the temperature sensitivity analysis

Sensitivity analysis for the experimental region was conducted using nine distinct temperature sets with 0.5^0 C, 1^0 C, and 1.5^0 C increments for the maximum and minimum temperatures both separately and together with 2019 climate data. The rest of the parameters remained unchanged. The DSSAT-CERES-Rice model was utilized to estimate rice yield under projected temperatures. The present values were compared with the estimated changes.

3.7. Experiment -7

Suitability analysis and rice yield prediction for Kozhikode and Palakkad districts under future climate scenarios

This study was conducted in the Kozhikode and Palakkad districts of Kerala. Palakkad is the prime district, which cultivates paddy in a larger area in Kerala and Paddy cultivation serves as a primary source of income for numerous farmers. However, the sustainability of paddy agriculture in the region faces imminent threats due to changing climate patterns, encompassing elevated temperatures, shifts in rainfall patterns, and an upswing in the frequency of extreme weather events. To tackle this challenge, an investigation was undertaken to identify viable adaptation strategies and assess the potential impacts of climate change on paddy production in both the Kozhikode and Palakkad areas.

3.7.1 Description of the study area

Kozhikode

Kozhikode, sometimes referred to as Calicut in English, is a literature city in the Indian state of Kerala that is located on the Malabar Coast. it is the 19^{th} largest metropolitan area in India and the second largest in Kerala and has been included as a literature city in

the Creative Cities Network (UCCN) of UNESCO. Kozhikode, situated in the Western Ghats of India, enjoys a tropical monsoon climate. The district's average annual temperature is 2.5 % higher than the national average, at 28.47 ºC (83.25 ºF). Every year, Kozhikode experiences 235.65 wet days (64.56 % of the time) and more than 2000 mm (8.03 inches) of precipitation. The local economy and farmers in Kozhikode are deeply concerned about the growing effects of climate change on paddy agriculture.

The Kozhikode district consists of a total of 12 blocks (Kozhikode, Vadakara, Thodannur, Thuneri, Kunnamangalam, Chelannur, Balusseri, Koduvally, Kunnumal, Melady, Pantalayani and Perambra) which are distributed in the low land, mid-land and up-land areas, of which Chelannur, Koduvally, Melady, and Thodannur contribute to the major paddy fields (Fig.3.30). According to data obtained from the Economics and Statistics Department, the area under paddy cultivation in the district which was 84466 ha in 1975- 76 has come down to 2097 ha in 2020-21. Each successive year during this period has seen a sharp decline in the area under rice cultivation. The goal of the study was to gain a thorough understanding of the region's agricultural sector in Kozhikode district and the possible effects of climate change.

Palakkad

The district of Palakkad is situated in southern India, positioned between the Nilgiri Hills and the Western Ghats. It is a well-known agricultural region in the state of Kerala, especially for its paddy agriculture. The Palakkad district has a mostly tropical environment all year round, with high temperatures and humidity. Farmers and the local economy in Palakkad are deeply concerned about the growing effects of climate change on paddy agriculture. With vast rice fields spread across six taluks—Alathur, Pattambi, Palakkad, Chittur, Mannarkkad, and Ottapalam—the Palakkad district in Kerala is acknowledged as the state's leading rice-growing region. According to data obtained from the Economics and Statistics Department, the area under paddy cultivation in the district which was 160855 ha in 1985- 86 has come down to 76754 ha in 2020-21, i.e., 52 % reduction in area of rice cultivation.

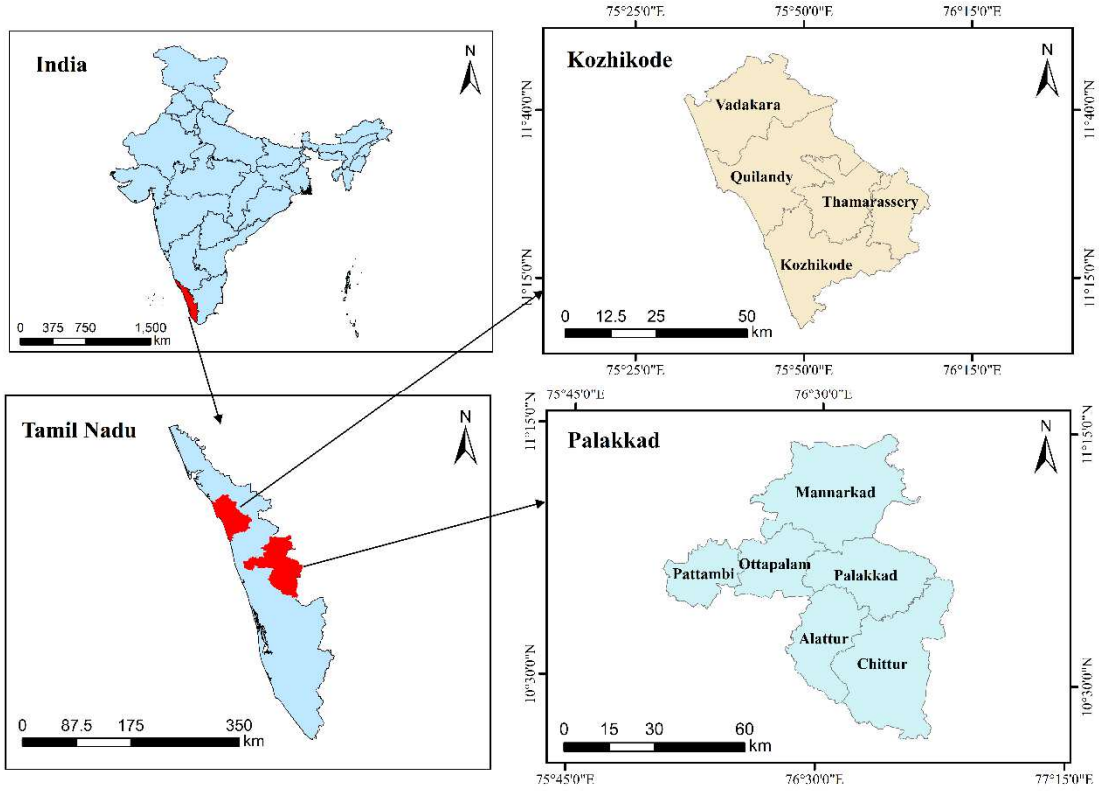


Fig.3.30. Study area map showing Kozhikode and Palakkad Districts

During the first crop season, remote sensing makes it challenging to detect rice fields due to severe interference from monsoon clouds. This approach was used in the second crop season (*Mundakan*) to determine suitability.

3.7.2. Crop Suitability for Paddy Cultivation in Kozhikode and Palakkad districts

Temperature and precipitation statistics for the Kozhikode and Palakkad district were gathered in relation to the climate. IMD GRIDDED was used to collect temperature data during a thirty-year span, from 1986 to 2020. Together with rainfall data from the same time period, this data was utilized to produce a paddy suitability map for the districts. In the case of Kozhikode district, throughout this 35-year period, the average annual precipitation approximately 3233 mm. An average range of 29–32 °C was found in the temperature data for the same period. For Palakkad district, the average annual precipitation ranged from a minimum of 1743 mm to a maximum of 2341 mm and an average range of 22–26 °C was found in the temperature data for the same period.

Many soil properties were extracted using the Kozhikode and Palakkad districts soil map, including soil type, texture, pH, slope, depth, drainage, and soil organic matter. These features were then contrasted with the previously provided soil suitability criterion table for rice in the Kozhikode and Palakkad districts (Table 3.17). The next step was to use ArcGIS software to reclassify these soil properties along with rainfall and temperature (Fig.3.31).

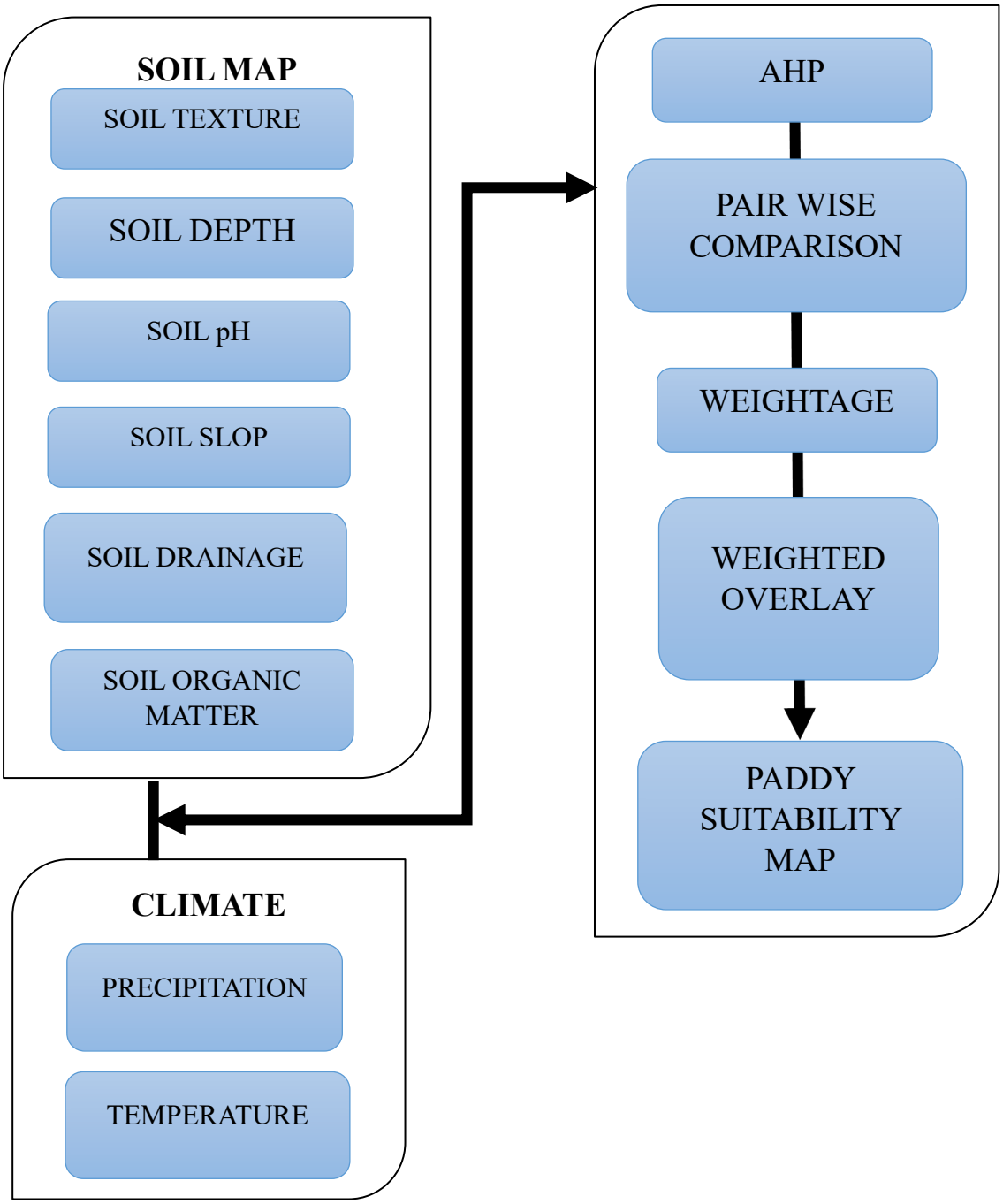


Fig. 3.31. Flowchart for paddy suitability

Table 3.17. Soil- site suitability criteria (crop requirement) for rice

SOIL – SITE CHARACTERISTICS			RATING			
		Unit	**Highly suitable S1**	**Moderately suitable S2**	**Marginally suitable S3**	**Not suitable N**
Climatic regime	**Mean temperature in growing season**	^{0}C	30 – 34	35 – 38 21 – 29	39 – 40 15 – 20	>40 <15
	Total rainfall	Mm	1110 – 1250	900 - 1110	750 – 900	<750
Land quality	**Land characteristics**					
Oxygen availability to roots	**Soil drainage**	Class	Imperfectly drained	Moderately well drained	Well drained: somewhat excessively drained	Excessively drained
	Free from flooding (duration)	month	>4	3 – 4	2 – 3	
	Depth of water	Cm	<10	10 – 20	>20 – 40	>40
Nutrient availability	**Texture**	Class	c, sic, cl, sicl, sc	scl, sil, l	sl, ls	s
	pH	1:2.5	5.5 – 6.5	6.4 – 7.5 4.5 – 5.4	7.6 – 8.5	>8.5 <4.5
	$CaCo_2$ in root depth	%	<15	15 – 75	25 – 30	>30
Rooting conditions	**Effective soil depth**	Cm	>75	51 – 75	25 – 50	<25
Soil toxicity	**Salinity (EC saturation extract)**	ds/m	<3	3 – 6	6 - 10	>10
	Sodicity (ESP)	%	<15	15 – 40	40 - 50	>50
Erosion hazard	**Slope**	%	0 – 1	1 – 3	3 – 5	>5

(Source: NBSS & LUP, 1990)

Flooding is conceded for rainfed rice

Note: s- sand; ls- loamy sand; sl- sandy loam; scl: sandy clay loam; cl: clay loam; sil: silt loam; l: loam; sic: silty clay; sc: sandy clay; c: clay

3.7.3. Yield Estimation

3.7.3.1 Data used

Numerous data types were used to estimate the paddy production in the district of Kozhikode. These include IMD GRIDDED temperature and precipitation data, MODIS Fraction of Photosynthetically Active Radiation (fAPAR) 8-day data from 2020, and 500-meter spatially resolved models MCD15A3H-061 and MCD18A3H-061. Additionally, multi-temporal data sets from Sentinel 2 with Bands 8 (NIR) and 11 (SWIR) were employed, as well as MODIS Photosynthetically Active Radiation (PAR) data from 2020.

3.7.3.2 AHP Method

The Analytical Hierarchy Process (AHP) method was employed in this study to ascertain the weights assigned to different data layers in the study region, aiming to identify suitable land for paddy production. Introduced by Saaty (1994, 1997), AHP is a multi-criteria decision-making approach known for its effective mathematical properties, widely utilized in various research studies. The method allows users to determine parameter weights in solving multi-criteria problems through a hierarchical model encompassing objectives, criteria, sub-criteria, and alternatives (Saaty, 1990). The study focused on analysing paddy crop data in Kozhikode and Palakkad districts, utilizing Geographic Information System (GIS) tools such as ArcGIS in conjunction with AHP. In the problem-solving process using Analytic Hierarchy Process (AHP), the method involves conducting pairwise comparisons to determine the relative importance of each criterion. This comparison matrix is then normalized to derive weights for each criterion. Normalization is achieved by dividing the elements in each column by the sum of that column. The outcome is a 'normalized pairwise comparison matrix,' which is subsequently utilized to compute a priority vector or weight vector. These weights fall within the range of 0 to 1 and collectively add up to 1, reflecting the relative significance of each criterion in the decision-making process.

The initial step involved determining criteria for evaluating the appropriateness of paddy production in the Kozhikode and Palakkad districts, encompassing factors like topography, soil quality, climate, and water availability. Pairwise comparisons were then conducted to assess the relative importance of each criterion. Spatial data for each criterion, such as soil maps and precipitation, were visualized and analysed using ArcGIS.

Raster layers were created for each criterion, categorized, and rescaled to a common scale (e.g., 1–10) for integration and comparison.

A measure of the consistency of pairwise comparisons is the consistency index in the AHP approach. The consistency ratio (CR) is crucial, aiming for a value less than or equal to 0.1 for a reliable analysis. CR is calculated by dividing the consistency index (CI) by the consistency index for a randomly produced matrix of the same size (RI). If CR exceeds 0.1, the variable is eliminated from the analysis.

$$CR = CI/RI$$

Where CR = consistency ratio

CI = consistency index

RI = consistency index for a random square matrix of the same size

The thematic maps were prepared using GIS software such as Soil Texture, Depth, Drainage, pH, DEM, Slope. The DEM and slope map was generated from SRTM DEM which was downloaded from USGS earth explorer with the resolution of 30 m. after creating thematic layers of each parameter need to reclassify according to the NBSS&LUP Soil site criteria which is mentioned in Table 3.17.

The next step involves considering the weightage of criteria. Employing the Weighted Sum tool in ArcGIS for a weighted overlay analysis involves the multiplication of each layer's values by their respective assigned weights, derived from the Analytical Hierarchy Process (AHP). The resultant raster is then normalized, yielding values within the range of 0 to 1. Following normalization, suitability categories, namely high, medium, and poor, are established.

Ultimately, a paddy suitability map is generated in ArcGIS based on the categorized raster. The map classifies areas as highly suitable, moderately suitable, marginally suitable, or not suitable for paddy cultivation. Farmers can identify the most suitable locations for paddy cultivation by applying the AHP approach, relying on precise spatial data and proficiency in GIS tools for data analysis and interpretation.

3.7.3.3. Current Scenario

The paddy land suitability map obtained using the AHP method can provide information on the areas that are most suitable for paddy cultivation in Kozhikode and

Palakkad districts. By combining this information with weather and soil data, along with crop growth models, we can estimate the average paddy yield for the current scenario in the region (Fig.3.32).

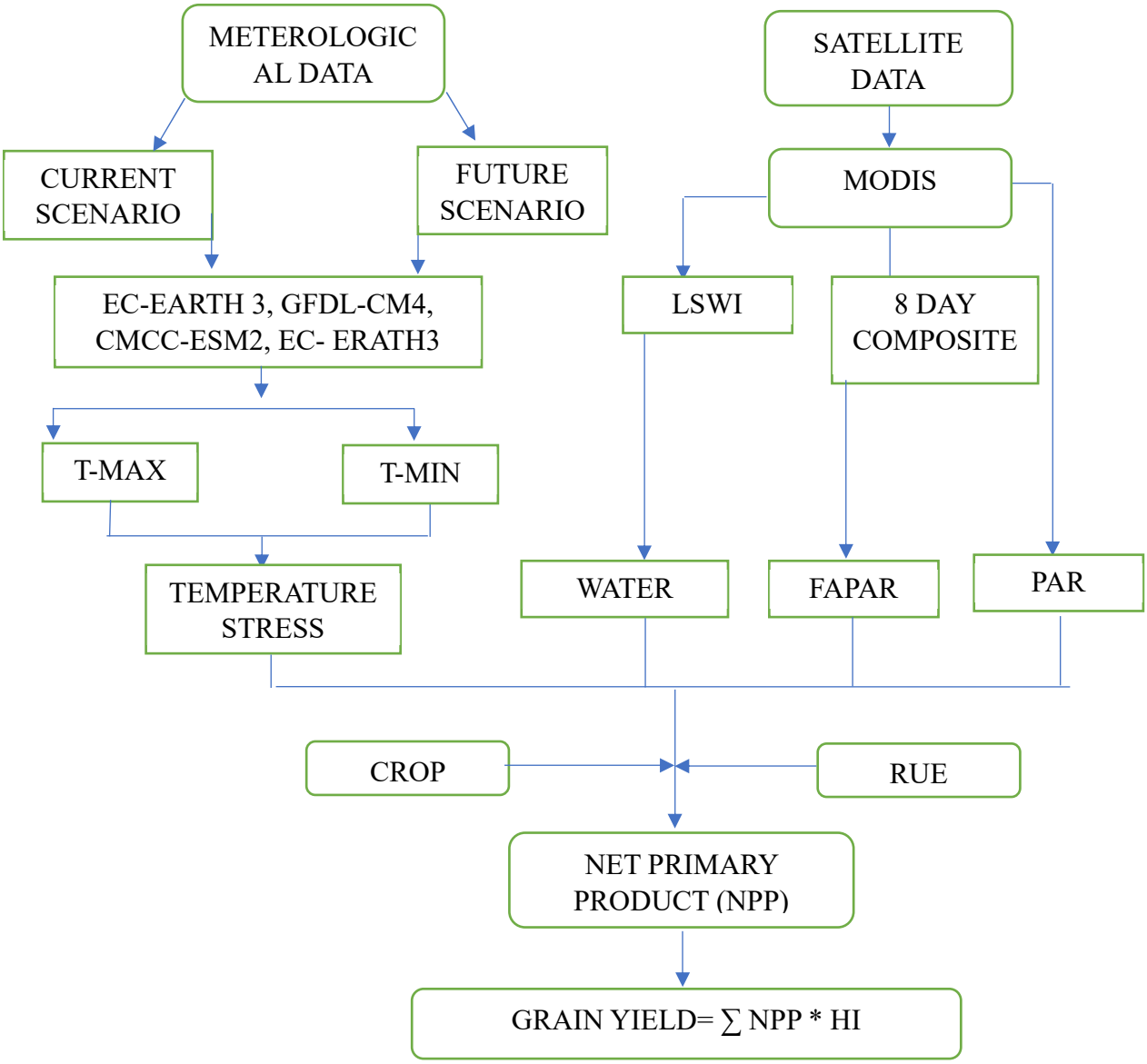


Fig.3.32. Flowchart of current and future yield prediction

This methodology is grounded in the concept that the biomass generated by a crop is influenced by the assimilation of photosynthetically active radiation (PAR), determined by the received light and the crop's ability to intercept PAR. To quantify the proportion of absorbed photosynthetically active radiation (fAPAR), Monteith's equation is employed in this approach. The ratio of absorbed PAR (APAR) to incident PAR is known as the fraction

of absorbed photo-synthetically active radiation (fAPAR), and it is limited between 0 and 1. The following diagram illustrates how incident PAR is converted into dry matter.

$$NPP_{g\,m^{-2}day^{-1}} = PAR * fAPAR * RUE$$

Where, PAR = Photosynthetically Active Radiation;

fAPAR = Fraction of Absorbed Photosynthetically Active Radiation

RUE = Radiation Use Efficiency.

For the *Mundakkan* paddy season, which runs from January to May 2020 with an 8-day temporal resolution, the Radiation Use Efficiency—which measures how well assimilated photo-synthetically active radiation (PAR) is used—as well as fAPAR and stress factors were computed. After looking at how temperature stress (Tstress) and water stress (Wstress) affected photosynthesis, the equation was changed to look like this:

$$NPP_{g\,m^{-2}day^{-1}} = PAR * fAPAR * RUE * W_{stress} * T_{stress}$$

3.7.3.3.1. Photo-synthetically Active Radiation (PAR)

The portion of the spectrum in sunlight between 400 and 700 nm is known as photosynthetically active radiation or PAR. Light is mostly absorbed by chlorophyll in narrow bands, having a maximum of 680 and 700 nm. Even though green light, which has a wavelength of about 550 nm, falls within the PAR area, more of it is reflected than the other wavelengths (W/m^2).

3.7.3.3.2. Fraction of Absorbed PAR (fAPAR)

Variations in species and ecosystems, human activity, weather and climate processes, and other factors all affect the variance of fAPAR over time and space. Myneni & Williams (1994) define fAPAR as the ratio of the amount of incident PAR absorbed by the vegetation to the amount of PAR assimilated by photosynthesizing tissue inside a canopy (Canopy Architecture and RS-IEEE.Pdf, n.d.). Terra-MODIS was used to obtain the fAPAR 8-day composite. The range of possible fAPAR values is 0 (no interception or absorption) to 1 (full interception or absorption).

3.7.3.3.3. Land surface water index (LSWI)

The Land Surface Water Index (LSWI) is a remote sensing-based vegetation index that can be used to assess surface water conditions in agricultural areas. It is particularly useful for monitoring water availability and estimating crop yields. LSWI is derived from satellite imagery and is sensitive to changes in both vegetation and water content in the soil.

The Near Infrared (NIR) and Shortwave Infrared (SWIR) portions of the electromagnetic spectrum are used to create the Land Surface Water Index, or LSWI, which is used to evaluate water stress. Both the total amount of plants and the moisture content of the soil affect this indicator.

$$\text{LSWI} = \frac{\text{NIR} - \text{SWIR}}{\text{NIR} + \text{SWIR}}$$

Where, NIR = Near Infrared

SWIR = Shortwave Infrared

To use LSWI for yield estimation, you can monitor changes in LSWI over time during the growing season. Increases in LSWI may indicate improved vegetation health due to sufficient water availability, while decreases may suggest water stress.

Water stress was also computed using the estimated LSWI (Xiao et al., 2005).

$$W_{stress} = \frac{1 - LSWI}{1 + LSWI_{max}}$$

Water stress assessment using the Land Surface Water Index (LSWI) involves monitoring changes in LSWI values over time to identify periods of water scarcity or excess. LSWI is sensitive to variations in both vegetation and water content in the soil, making it a valuable tool for detecting water stress in agricultural areas.

3.7.3.3.4. Temperature stress

Agro-climatic variables like Temperature Stress have been used to create spectral yield models for the paddy crop (Rugira et al., 2021). The formula for calculating temperature stress is given below:

$$T_{stress} = \frac{(T - T_{min})(T - T_{max})}{(T - T_{min})(T - T_{max}) - (T - T_{opt})^2}$$

where:

T= actual temperature

Tmin = Minimum temperature for photosynthesis(°C)

Tmax = Maximum temperature for photosynthesis(°C)

Topt = Optimal temperature for photosynthesis(°C)

T = Daily mean temperature (°C)

The ratio of grain yield to total biomass is called the Harvest Index (HI). Grain yield is therefore the result of multiplying the harvest index (HI) by the net primary productivity (NPP).

$$\text{Grain Yield} = \text{NPP} * \text{HI}$$

Where, HI= harvest index (HI)

NPP= net primary productivity (NPP).

The LSWI, PAR, and fAPAR data are processed through the paddy crop mask in order to get the overall NPP. After that, the average pixel yield is calculated, and the average district-level yield is ascertained from there.

3.7.3.4. Future scenario

In order to model future climate conditions, our study used climate data from six GCMs taking part in the Coupled Model Intercomparison Project's sixth phase (CMIP6). The Coupled Model Intercomparison Project Phase 6 (CMIP6) plays a pivotal role in advancing our understanding of the Earth's climate system and refining projections for future climate conditions. These models simulate the intricate interactions within the atmosphere, ocean, land surface, and ice components of the Earth's climate. A primary objective of CMIP6 is to facilitate a comprehensive intercomparison of these models, allowing scientists to assess their performance in simulating historical climate patterns. The Coupled Model Intercomparison Project Phase 6 (CMIP6) incorporates five major scenarios (SSP 1-1.9 to SSP 5-8.5) known as Shared Socioeconomic Pathways (SSPs), each offering a distinct narrative for potential future societal, economic, and technological trajectories. In this study, CMCC-ESM2, EC-Earth3, EC-Earth3-Veg, and GFDL-CM4,

are all climate models used in scientific research to simulate and study Earth's climate system.

1. CMCC-ESM2 (Centro Euro-Mediterraneo sui Cambiamenti Climatici Earth System Model 2)

2. EC-Earth3 (European Consortium Earth System Model 3)

3. EC-Earth3-Veg (European Consortium Earth System Model 3 with vegetation)

4. GFDL-CM4 (Geophysical Fluid Dynamics Laboratory Climate Model 4).

Temperature data from CMPI6 SSP 2-4.5 and SSP 5-8.5 of 4 models were used in addition to the data sources used for the current scenario. This will enable us to project how future climate change will impact the districts of Kozhikode and Palakkad paddy crops. To forecast the possible effects of future climate change on paddy yields, the data from these models can be integrated into the crop growth models utilized for the current scenario.

In order to model future climate conditions, our study used climate data from four GCMs taking part in the Coupled Model Inter-comparison Project's sixth phase (CMIP6). Modelling organizations from all across the world are working together on CMIP6, or Coupled Model Inter-comparison Project Phase 6, which aims to produce accurate predictions of future climate change and advance our understanding of the Earth's climate system. The Earth's climate system is simulated by a collection of revolutionary climate models that take into account physical, chemical, and biological processes. We specifically looked at SSP 2-4.5 and SSP 5-8.5, two distinct representative concentration routes (SSPs) and similar socioeconomic pathways. SSP 5-8.5 and SSP 2-4.5 are two examples of these cases. A future envisioned by SSP 2-4.5 (Shared Socioeconomic Pathway 2-4.5) shows a peak in greenhouse gas emissions in the middle of the twenty-first century, followed by a decrease when low-carbon technology and policies are adopted. On the other hand, SSP 5-8.5 (Shared Socioeconomic Pathway 5-8.5) depicts a scenario in which there are no appreciable attempts made to reduce greenhouse gas emissions, and emissions rise throughout the 21st century. With the use of these scenarios, scientists can look at the potential effects of various greenhouse gas emission paths on future climate change and its related effects. In order to estimate future paddy yields under climate change scenarios, we employed four climate models that took part in the sixth phase of the Coupled Model Inter-comparison Project (CMIP6). The CMCC-ESM2, EC-Earth3, EC-Earth3-Veg and

GFDL-CM4 models were among them. We examined the anticipated climate changes for each model and estimated future paddy yields under the SSP 2-4.5 and SSP 5-8.5 scenarios.

The current scenario's technique was applied to the future situation with minor adjustments. Temperature data from CMPI6 SSP245 and SSP584 of 5 models were used in addition to the data sources used for the current scenario. This will enable us to project how future climate change will impact the districts' (Kozhikode and Palakkad) paddy crops. To forecast the possible effects of future climate change on paddy yields, the data from these models can be integrated into the crop growth models utilized for the current scenario.

3.7.4. Adaption strategies for improving the rice production

The validated DSSAT-CERES-Rice model was used to run different scenarios and assess the viability of various adaptation techniques aimed at enhancing rice yield. The sensitivity analysis scenario used for this simulation experimental with nine distinct temperature sets with $0.5\ ^0$ C, $1\ ^0$ C, and $1.5\ ^0$ C increments for the maximum and minimum temperatures both separately and together of 2019 climate data. The rest of the parameters remained unchanged. One of the adaption strategies taken into consideration is altering the date of sowing and transplanting. The DSSAT-CERES model was run for five days of early sowing and five days of late sowing in order to assess the effects of changing the planting date. Another adaptation strategy was increasing the N content of the fertilizer by 150 %. Tests were conducted to see how rice yields responded to various transplanting and seeding dates. To compare the observed crop yield, the simulated values were used.

Results

4. Results

The purpose of this research was to determine the best management strategies for rice with respect to its water and nutrient demand for optimal growth and production. This was achieved through a series of field experiments, crop modelling, and simulation studies. Additionally, the study aimed to assess the impact of various environmental factors on rice growth and production under different climate scenarios. This chapter presents and interprets the findings from the field and laboratory research conducted during the course of the investigation, which were designed to address the objectives of the study. The experiments specifically examined the effects of various treatments on water and nutrient management on growth indicators and yields of rice in the context of changing climate conditions.

4.1. Experiment -1

The first experiment was designed to evaluate the effect of different nutrient management and method of irrigation on four different rice varieties, commonly cultivated in Kerala, on rice growth parameters. The results acquired from the research work entitled "*Assessing the influence of nutrient management and method of irrigation on biometric characters of four different rice cultivars"* were elucidated here.

4.1.1. Experimental soil and site characteristics

The experimental soil belongs to lateritic and taxonomically named as *Mixed; Isohyperthermic, Typic Kanhaplustults as per USDA and known as* Kunnamangalam. Initial soil physico- chemical parameters of the experimental plot are tabulated in Table 4.1. The experimental soil has pH of 6.56, organic carbon of 1.05 %, available N of 213.6 kg ha^{-1}, available P of 26.5 kg ha^{-1} and available K of 113.12 kg ha^{-1}. The soils possess the field capacity of 32.67 % and wilting point of 14.34 %, respectively.

4.1.2. Climatic parameters

The experimental site experiences a humid tropical climate characterized by hot, dry summers and cold winter seasons The maximum temperature experienced in the experimental location during the crop growth period was 35.0 ^{0}C and the minimum temperature that prevailed during the experimental period was 16.0 ^{0}C, respectively. Throughout the crop growth period, the total rainfall received was 460.8 mm. Average maximum relative humidity and minimum relative humidity were found to be 98.0 % and

62.0 % respectively during the experimental period. Weather parameters experienced during the experimental period are graphically represented in Fig.4.1.

Table 4.1. Soil physico- chemical parameters of experimental plot

Soil parameters	Values
pH	6.56
Organic carbon (%)	1.05
Soil -Available N (kg ha^{-1})	213.60
Soil- Available P (kg ha^{-1})	26.50
Soil-Available K (kg ha^{-1})	113.12
Field capacity (%)	32.67
Wilting point (%)	14.34

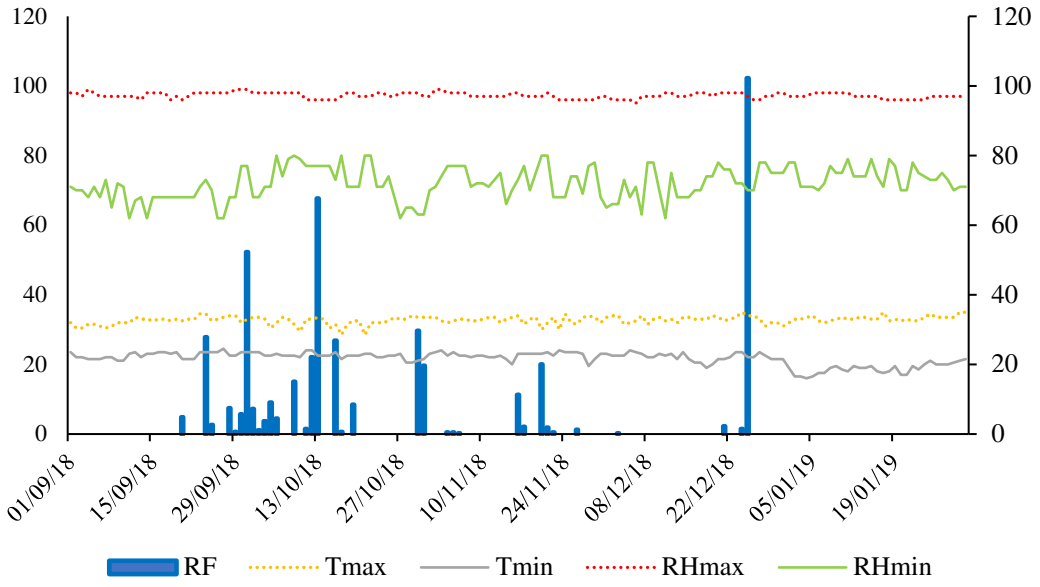


Fig.4.1. Weather data during crop growth period- Experimental 1

4.1.3. Biometric characteristics

In this study, the focus is exclusively on morphological parameters as key indicators to represent the developmental aspects of plants as influenced by the treatments. Morphological parameters refer to the physical characteristics and structural features of plants that can be visually observed and measured. Morphological characteristics of the plant, *viz.*, height of the plant, the number of tillers, and the number of panicles of each variety were measured during all three stages.

Plant height

The observed plant heights of different varieties are represented in Table 4.2. Results showed that both water and nutrient management treatments had a statistically significant effect on plant height in this experiment. In the case of *Jyothi* cultivar, among the three growth stages of rice, only the panicle initiation stage (60 DAT) showed a significant effect of irrigation treatments on plant height. Plants grown under flooded fields showed higher values for plant height than plants grown in Alternative Wetting and Drying (AWD) fields. However, in the case of different levels of N application treatments, a significant effect was noticed in plant height during the tillering and panicle initiation stages, beyond that there was no effect. The flooded condition with N3 treatment has the highest values for plant height in the initial stage, i.e., 51.0±2.7 cm. It was followed by N2 treatment (45.0±8.7 cm) and N1 treatment (42.7±12.2 cm). In the AWD condition also, N3 treatment has the highest values for pant height in the initial stage, i.e., 44.7±4.0 cm. It was followed by N2 treatment (42.7±4.7 cm) and N1 treatment (41.7±5.7 cm). During the panicle initiation period (60th day after planting), the highest plant height (81.3±7.1cm) was observed in N3 treatment under flooded conditions, which was followed by 72.7±9.5 cm for N2 treatment and 61.7±2.9 cm for N1 treatment. In the AWD condition, the highest plant height was observed for the N3 treatment (64.7±4.0 cm), which was followed by the N2 treatment (62.7±4.6 cm) and the least value was noticed in the N1 treatment (61.7±5.8 cm). Then during the maturation stage (105th day after planting), N3 treatment had the highest values for plant height i.e., 87.4±5.5 cm, which was followed by N2 treatment (77.0±10.3 cm) and N1 treatment (77.0±14.7 cm) for flooded condition. In the AWD condition also, N3 treatment has the highest values for plant height in the maturity stage, i.e., 73.6±4.4 cm. It was followed by N2 treatment (71.9±4.7 cm) and N1 treatment (71.0±8.8 cm). The interaction effect of irrigation and nutrient application on plant height was found to be non-significant.

In the case of *Jaya* paddy variety, both the panicle initiation stage and the maturity stage had a significant impact on the irrigation treatments. Flooded plants performed better than AWD-treated plants. Among the three developmental stages (active tillering observed during 30 DAT, panicle initiation observed during 60 DAT, and maturation stage observed during 105 DAT) of rice, different percentages of N applications had a significant impact on plant height in *Jaya* cultivars. Among them, the T3 treatment with the highest content

Table 4.2. Plant height of four different rice varieties, are represented as Mean ± Standard Deviation (SD) of three replications.

Treatment		V1			V2			V3			V4		
		30 DAT	**60 DAT**	**105 DAT**	**30 DAT**	**60 DAT**	**105 DAT**	**30 DAT**	**60 DAT**	**105 DAT**	**30 DAT**	**60 DAT**	**105 DAT**
	I1N1	42.7±12.2	61.7±2.9	77.0±14.7	46.0±5.2	69.6±0.7	73.8±1.1	35.7±4.7	39.3±4.9	42.1±3.7	59.3±4.0	61.7±2.9	65.3±4.9
	I1N2	45.0±8.7	72.7±9.5	77.0±10.3	61.7±5.7	74.0±4.5	77.9±4.5	40.7±2.3	46.7±6.5	48.3±4.0	61.8±5.5	68.3±11.6	71.7±6.5
	I1N3	51.0±2.7	81.3±7.1	87.4±5.5	65.7±4.9	80.9±1.9	86.1±2.3	45.3±0.6	50.7±2.5	53.7±4.3	67.5±4.3	71.7±2.1	73.7±2.5
	I2N1	41.7±5.7	61.7±5.8	71.0±8.8	49.7±5.7	62.3±0.6	65.5±0.6	31.7±9.6	34.3±7.6	40.3±2.3	51.7±1.2	57.3±2.1	63.1±2.1
	I2N2	42.7±4.7	62.7±4.6	71.9±4.7	60.7±5.5	71.1±4.8	74.9±4.8	38.0±3.6	42.0±2.7	44.7±1.2	56.3±2.3	63.7±1.2	69.3±4.0
	I2N3	44.7±4.0	64.7±4.0	73.6±4.4	61.0±1.3	76.0±3.6	79.9±3.6	41.7±0.5	46.0±3.0	49.3±2.3	63.3±3.7	69.7±0.6	71.3±2.3
I	**SE(m)**	2.4	2	4.2	1.7	1	1.1	1.3	1.3	1.6	1.3	1.3	2.4
	CV	15.3	8.9	11.6	10.1	4.2	4.3	6.9	5.8	7.3	6.1	5.8	12.5
	CD	-	6.2	-	-	3.2	3.5	4.8	3.9	4.9	-	3.9	7.4
N	**SE(m)**	2.3	2.5	5.1	2.1	1.3	1.3	1.6	1.5	1.9	1.6	1.5	2.9
	CV	15.3	8.9	11.6	10.1	4.2	4.3	6.9	5.8	7.3	6.1	5.8	12.5
	CD	8.9	7.6	-	6.7	3.9	4.2	5.1	4.9	6	-	4.7	9.1
I X N	**SE(m)**	4.1	4.9	5.1	2.9	1.8	1.9	2.3	2.2	2.7	2.2	2.2	4.2
	CV	15.3	8.9	11.6	10.1	4.2	4.3	6.9	5.8	7.3	6.1	5.8	12.5
	CD	-	-	-	-	-	-	-	-	-	-	-	-
Fvalue	**I**	NS	**	NS	NS	**	**	*	*	**	NS	*	**
	N	*	*	NS	**	**	**	*	**	**	NS	**	*
	I X N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Where, V1 is *Jyothi*, V2- *Jaya*, V3- *Uma*, V4- *Kanchana*, I1 is waterlogged/ flooded, I2 is alternate wetting and drying (AWD), N1 is 0 % application of the recommended dose of nutrients, N2 is 100 % application of the recommended dose of nutrients (RDN) through inorganic fertilizers and N3 is 120 % N of the RDN through inorganic fertilizers. Significance at P< 0.05 * and P>0.01 **, LSD test.

of nitrogen fertilizer application had the highest plant height. There was no combined influence of irrigation and fertilizer control on plant height. The flooded condition with N3 nitrogen treatment has the highest values for plant height in the initial stage, i.e., 65.7±4.9 cm. It was followed by N2 treatment (61.7±5.7 cm) and N1 treatment (46.0±5.2 cm). In the AWD condition also, N3 treatment has the highest values for plant height in the initial stage, i.e., 61.0±1.3 cm. It was followed by N2 treatment (60.7±5.5 cm) and N1 treatment (49.7±5.7 cm). During the panicle initiation period (60th day after planting), the highest average values for plant height for flooded conditions were seen for N3 treatment (80.9±1.9 cm), which was followed by N2 treatment (74.0±4.5 cm) and N1 treatment (69.6±0.7 cm). In the AWD condition highest plant height was noticed for the N3 treatment (76.0±3.6 cm), then for N2 treatment (71.1±4.8 cm) and the lowest value was observed for N1 treatment (62.3±0.6 cm). Then during the maturation stage (105th day after planting), N3 treatment has the highest values for plant height, i.e., 86.1±2.3 cm, which was followed by N2 treatment (77.9±4.5 cm) and N1 treatment (73.8±1.1cm) for flooded condition. In the AWD condition also, N3 treatment has the highest values for plant height in the maturation stage, i.e., 79.9±3.6 cm. It was followed by N2 treatment (74.9±4.8 cm) and N1 treatment (65.5±0.6 cm).

Among the three growth stages of the Uma rice variety in this experiment, different water management practices and percentages of N applications had a significant impact on plant height, but they lacked the combined interaction effect. In the Uma rice variety, flooded condition with N3 nitrogen treatment has the highest values for plant height in the initial stage, i.e., 45.3±0.6 cm. It was followed by N2 treatment (40.7±2.3 cm) and N1 treatment (35.7±4.7 cm). In the AWD condition also, N3 treatment has the highest plant height in the initial stage, i.e., 41.7±0.5 cm. It was followed by N2 treatment (38.0±3.6 cm) and N1 treatment (31.7±9.6 cm). During the panicle initiation period (60th day after planting), the highest average values for plant height for flooded conditions were seen in N3 treatment (50.7±2.5 cm), which was followed by N2 treatment (46.7±6.5 cm) and N1 treatment (39.3±4.9 cm), respectively. In the AWD condition highest plant height was measured for N3 treatment (46.0±3.00 cm), then for N2 treatment (42.0±2.7 cm) and the least value was observed for N1 treatment (34.3±7.6 cm). Then at the maturity stage (105th day after planting), N3 treatment has the highest plant height, i.e., 53.7±4.3 cm, which was followed by N2 treatment (48.3±4.0 cm) and N1 treatment (42.1±3.7 cm) for flooded condition. In the AWD condition also, N3 treatment has the highest values for plant height

in the maturity stage, i.e., 49.3±2.3 cm. It was followed by N2 treatment (44.7±1.2 cm) and N1 treatment (40.3±2.3 cm).

For the *Kanchana* rice variety, except tillering, both the panicle initiation stage and the maturity stage had a significant impact on the irrigation treatments as well as the nutrient treatments. Flooded plants with N3 treatment performed better than other treatments in all three stages. The interaction effect was found to be non-significant. In the *Kanchana* rice variety, the flooded condition N3 treatment has the highest values for plant height in initial stage, i.e., 67.5±4.3 cm. It was followed by N2 treatment (61.8±5.5 cm) and N1 treatment (59.3±4.0 cm). In the AWD condition also, N3 treatment has the highest values for plant height in the initial stage, i.e., 63.3±3.7 cm. It was followed by N2 treatment (56.3±2.3 cm) and N1 treatment (51.7±1.2 cm). During the panicle initiation period (60^{th} day after planting), the highest plant height for flooded conditions were seen for N3 treatment (71.7±2.1 cm), which was followed by N2 treatment (68.3±11.6 cm) and N1 treatment (61.7±2.9 cm). In the AWD condition highest plant height was measured for N3 treatment (69.7±0.6 cm), then for N2 treatment (63.7±1.2 cm) and the least value was observed for N1 treatment (57.3±2.1 cm). Then during the maturation stage (105^{th} day after planting), N3 treatment has the highest values for plant height, i.e., 73.7±2.5 cm, which was followed by N2 treatment (71.7±6.5 cm) and N1 treatment (65.3±4.9 cm) for flooded condition. In the AWD condition also, N3 treatment has the highest values for plant height, i.e., 71.3±2.3 cm. It was followed by N2 treatment (69.3±4.0 cm) and N1 treatment (63.1±2.1 cm), respectively.

Number of tillers

Among the two different irrigation methods, waterlogged/ flooded condition has the highest number of tillers when compared to the AWD irrigation method and it was statistically significant at various stages of paddy growth. Observed tiller numbers of different varieties are represented in Table 4.3. In the case of *Jyothi* variety, all three stages of the crop's development were found to be significantly effective with N application treatments but in the different water management treatments except the tillering stage, other stages were significantly impacted by the treatment. However, there was no combined influence observed for irrigation and nutrient application on number of tillers.

Flooded condition with N3 treatment has the highest values for the number of tillers in the initial stage, i.e., 6.3±0.6 and the least in N1 treatment (4.0±1.0). In the AWD condition also, N3 treatment had the highest number of tillers in the initial stage, i.e.,

5.3±0.6. and the least in N1 treatment (3.7±1.3). At the panicle initiation stage (60th day after planting), the highest number of tillers for the flooded condition was 10.0±2.6 for N3 treatment, which was followed by 7.0±1.0 for N2 treatment and 5.7±0.6 for N1 treatment, respectively, and the treatments showed significant influence. In the AWD condition, the highest number of tillers was observed for N3 treatment (7.0±1.0), which was followed by N2 treatment (5.3±1.2) and N1 treatment (5.3±0.6), respectively. Final measurements were taken during the 105th day after planting during the maturation stage. In the flooded condition, N3 treatment has the highest number of tillers, i.e., 9.0±1.0 and the least for N1 treatment (5.5±0.6). In the AWD condition also, N3 treatment has the highest number of tillers, i.e., 7.3±0.6 and the least for N1 treatment (3.3±0.6) and showed a significant difference between the applied treatments.

In the case of *Jaya* variety, treatment for water management and N application had a significant impact on the active tillering stage and also in the next two stages but, here also, there were no combined influences observed for irrigation and nutrient application on number of tillers. In the flooded condition N3 and N2 treatment have the highest values for number of tillers in the initial stage, i.e., 6.7±0.3 and 6.7±0.6 respectively. It was followed by N1 treatment (4.3±1.2). In the AWD condition, N2 treatment had the highest values for number of tillers in the initial stage, i.e., 5.0±0.2. It was followed by N3 treatment (4.7±0.6) and N1 treatment (4.3±1.2). After 60th day of planting during the panicle initiation stage, the highest average number of tillers for flooded conditions was 10.0±2.0 for the N3 treatment, which was followed by 7.7±1.2 for the N2 treatment and 5.7±0.6 for the N1 treatment. In the AWD condition, the highest number of tillers were observed for N3 treatment (7.3±0.6) which is followed by N2 treatment (6.3±0.6) and N1 treatment (4.7±0.6). During the maturation period, the flooded condition with N2 treatment has the highest values for number, i.e., 7.0±1.7. It was followed by N3 treatment (6.3±0.6) and the least for the N1 treatment (4.7±0.6). In the AWD condition also, the N2 treatment has the highest values for number of tillers, i.e., 5.7±1.2. It was followed by the N3 treatment (5.0±0.0) and the least for the N1 treatment (4.3±0.6) and showed a significant difference between the applied treatments.

The *Uma* rice variety also was found to be significantly influenced by water management and N fertilizer management, both alone and in combinations in all states except the tillering stage, in which the interaction effect was found to be non-significant. The flooded (I1) condition with high nitrogen level (T3) treatment produced the highest

Table 4.3. Number of tillers of four different rice varieties, are represented as Mean ± Standard Deviation (SD) of three replications.

Treatment		V1			V2			V3			V4		
		30 DAT	**60 DAT**	**105 DAT**	**30 DAT**	**60 DAT**	**105 DAT**	**30 DAT**	**60 DAT**	**105 DAT**	**30 DAT**	**60 DAT**	**105 DAT**
	I1N1	4.0±1.0	5.7±0.6	5.5±0.6	4.3±1.2	5.7±0.6	4.7±0.6	4.0±1.0	4.7±0.6^{c}	4.7±0.6^{c}	5.3±0.6	6.3±0.6	6.3±0.6
	I1N2	5.3±0.6	7.0±1.0	6.7±0.6	6.7±0.6	7.7±1.2	7.0±1.7	5.3±1.2	6.7±0.6^{b}	6.7±0.6^{b}	6.7±0.6	7.7±1.5	7.7±1.5
	I1N3	6.3±0.6	10.0±2.6	9.0±1.0	6.7±0.3	10.0±2.0	6.3±0.6	8.3±1.2	10.0±1.0^{a}	9.0±1.0^{a}	6.7±0.6	11.0±1.0	11.0±1.0
	I2N1	3.7±1.3	5.3±0.6	3.3±0.6	4.3±1.2	4.7±0.6	4.3±0.6	3.3±0.6	5.3±0.6 ^{bc}	5.3±0.6 ^{bc}	4.3±0.6	5.3±0.7	5.3±0.7
	I2N2	5.0±1.0	5.3±1.2	5.3±1.7	5.0±0.2	6.3±0.6	5.7±1.2	3.3±0.6	5.3±0.6^{bc}	5.3±0.6^{bc}	6.0±1.0	7.7±0.6	7.7±0.6
	I2N3	5.3±0.6	7.0±1.0	7.3±0.6	4.7±0.6	7.3±0.6	5.0±0.0	6.0±1.0	6.3±1.2^{b}	6.3±0.6^{b}	6.0±1.0	9.7±0.6	9.7±0.6
I	**SE(m)**	0.31	0.45	0.31	0.26	0.36	0.27	0.31	0.27	0.21	0.27	0.31	0.31
	CV	19.07	20.142	14.5	14.54	15.48	14.85	16.65	12.673	10.21	13.64	11.64	11.64
	CD	-	1.39	0.97	0.81	1.13	0.86	0.97	0.85	0.66	-	-	-
N	**SE(m)**	0.54	0.55	0.38	0.31	0.43	0.33	0.38	0.33	0.26	0.33	0.38	0.38
	CV	19.07	20.14	14.51	14.54	15.48	14.85	16.65	12.67	10.21	13.64	11.64	11.64
	CD	1.19	2.18	1.19	0.99	1.38	1.05	1.19	1.04	0.8	1.02	1.19	1.19
I X N	**SE(m)**	0.54	0.78	0.54	0.44	0.621	0.47	0.53	0.47	0.36	0.46	0.53	0.53
	CV	19.07	20.14	14.51	14.54	15.48	14.85	16.65	12.67	10.21	13.64	11.64	11.64
	CD	-	-	-	-	-	-	-	1.47	1.14	-	-	-
Fvalue	**I**	NS	*	**	**	**	*	*	**	*	NS	NS	NS
	N	*	**	**	*	**	**	**	**	**	*	**	**
	I X N	NS	NS	NS	NS	NS	NS	NS	**	**	NS	NS	NS

Where, V1 is *Jyothi*, V2- *Jaya*, V3- *Uma*, V4- *Kanchana*, I1 is waterlogged/ flooded, I2 is alternate wetting and drying (AWD), N1 is 0 % application of the recommended dose of nutrients, N2 is 100 % application of the recommended dose of nutrients (RDN) through inorganic fertilizers and N3 is 120 % N of the RDN through inorganic fertilizers. Significance at P< 0.05 * and P>0.01 **, LSD test.

number of tillers in both the panicle initiation stage and the maturity stage, i.e., 10.0±1.0 and 9.0±1.0 respectively, and it was found to be the superior treatment. Whereas, the inferior one among the treatments was I1T1 treatment in the panicle initiation stage and the maturity stage, 4.7±0.6 and 4.7±0.6, respectively. The treatments I2 N1 and I2N2 were statistically on par in both the panicle initiation and the maturation stage.

In the case of the rice cultivar *Kanchana*, different levels of N treatments were statistically significant during all three growth stages in this experiment. However, the irrigation treatments failed to significantly influence the number of tillers in this experiment. The N3 and N2 nitrogen treatment have the highest number of tillers in the initial stage, i.e., 6.7±0.6. It was followed by N1 treatment (5.3±0.6). In the AWD condition also, N3 and N2 treatments have the highest values for the number of tillers in the initial stage, i.e., 6.0±1.00. It was followed by N1 treatment (4.3±0.6). At the panicle initiation stage, the average number of tillers for flooded conditions was 11.0±1.0 for N3 treatment, 7.7±1.5 for N2 treatment and 6.3±0.6 for N1 treatment, respectively. In AWD condition number of tillers was 9.7±0.6 for N3 treatment, 7.7±0.6 for N2 treatment and 5.3±0.7 for N1 treatment. Final measurements were taken during the 105th day after planting during the maturation stage. In the flooded condition, the N3 treatment had the highest number of tillers, i.e., 11.0±1.0. It was followed by N2 treatment (7.7±1.5) and N1 treatment (6.3±0.6). In the AWD condition also, the N3 treatment had the highest number of tillers in the maturity stage, i.e., 9.7±0.6. It was followed by N3 treatment (7.7±1.5) and N1 treatment (6.3±0.6), respectively.

Leaf area index (LAI)

The leaf area index (LAI) calculated during the experiments is tabulated in Table 4.4. In the case of the *Jyothi* rice variety, nitrogen application treatments had impacted the LAI during all three stages, whereas in water management treatments only the tillering stage had an impact on LAI. However, there was no interaction effect of irrigation and nutrient management treatments and it was non-significant. Among the treatments, I2N1 (0.8±0.3) had the least LAI during the tillering stage and the highest was noticed in the I1N3 treatment (2.6±0.3). After 60^{th} day of transplanting, the highest average value for LAI of flooded conditions was 4.4±0.5 for N3 treatment, which was followed by 3.3±0.3 for N2 treatment

and 2.9±0.5 for N1 treatment. In the AWD condition, the highest LAI was observed for N3 treatment (3.9±0.5), which was followed by N2 treatment (2.4±0.0) and N1 treatment (2.5±0.8), respectively. A similar trend was observed at the maturity stage also, which showed that the N3 treatment recorded the highest values for LAI both in flooded and AWD irrigated plants, i.e., 3.8±0.5 & 3.2±0.9, and the least for the N1treatments, 2.2±0.6 & 0.9±0.1 respectively.

Throughout the experiment*, Jaya* rice varieties had shown a significant effect on the LAI by managing the water and nutrient treatments, but the combined effect was found to be non-significant. In the *Jaya* rice cultivar, the flooded condition with N3 nitrogen treatment had the highest values for LAI in all three rice growth stages. Among them, the panicle initiation stage had the highest value for I1N3 (4.1±0.7) and the lowest values was observed during the tillering stage for I2N1 treatment (0.6±0.3). In the tillering stage, the highest was noticed for I1N3. Then during the maturity, stage N3 treatment had the highest values for LAI both in flooded and AWD irrigated plants, i.e., 3.4±0.4 & 2.5±0.5 respectively, and the least for N1treatments (1.9±0.4 & 0.8±0.3 respectively).

Nitrogen application treatments and water management in *Uma* rice variety had a significant effect on LAI at all three stages, except for water management treatment during tillering. However, irrigation and nutrient management interaction was non-significant. Among the treatments, I1N3 (2.3±0.4) had the highest LAI during the tillering stage, followed by I1N2 and I2N3 treatments (1.8±0.3) and I2N2 treatment (1.6±0.1). Whereas the lowest was for I1N3 (1.0±0.1), followed by I1N1 treatment (1.2±0.1). At the panicle initiation stage, the highest values of LAI for flooded conditions were found in the N3 treatment (4.4±0.5), which was followed by 3.3±0.3 for the N2 treatment and 2.9±0.5 for the N1 treatment. In AWD condition highest LAI was observed for N3 treatment (3.3±0.5), which was followed by N2 treatment (2.9±0.5) and then N1 treatment (2.7±0.6). Then during the maturation stage, N3 treatment had the highest values for LAI both in flooded and AWD irrigated plants, i.e., 3.4±0.2 & 2.9±0.1, and least for N1treatments, 2.9±0.1 & 2.6±0.1 respectively.

Table 4.4. Leaf area index of four different rice varieties, are represented as Mean ± Standard Deviation (SD) of three replications.

		V1			V2			V3			V4		
Treatment		**30 DAT**	**60 DAT**	**105 DAT**	**30 DAT**	**60 DAT**	**105 DAT**	**30 DAT**	**60 DAT**	**105 DAT**	**30 DAT**	**60 DAT**	**105 DAT**
	I1N1	1.2±0.4	2.9±0.5	2.2±0.6	1.2±0.6	2.1±0.1	1.9±0.4	1.2±0.1	2.9±0.0	2.6±0.1	1.9±0.3	2.7±0.3	1.9±0.8
	I1N2	2.1±0.9	3.3±0.3	2.8±0.4	1.9±0.1	2.7±0.3	2.7±0.2	1.8±0.3	3.3±0.5	2.9±0.2	1.7±0.4	2.8±1.1	2.5±0.8
	I1N3	2.6±0.3	4.4±0.5	3.8±0.5	2.7±1.8	4.1±0.7	3.4±0.4	2.3±0.4	4.4±0.3	3.4±0.2	2.3±0.2	3.8±0.5	3.1±1.1
	I2N1	0.8±0.3	2.5±0.8	0.9±0.1	0.6±0.3	1.7±0.4	0.8±0.3	1.0±0.1	2.7±0.6	2.3±0.1	0.9±0.3	2.4±0.8	1.8±0.9
	I2N2	1.1±0.2	2.4±0.0	1.8±0.9	1.8±0.2	2.3±0.1	1.5±0.3	1.6±0.1	2.9±0.5	2.5±0.1	1.7±0.2	2.4±0.5	2.1±0.4
	I2N3	2.1±0.5	3.9±0.5	3.2±0.9	2.2±0.3	3.2±0.7	2.5±0.5	1.8±0.3	3.3±0.5	2.9±0.1	2.3±0.8	3.4±0.9	2.8±1.2
I	**SE(m)**	0.19	0.21	0.17	0.11	0.16	0.13	0.13	0.15	0.054	0.39	0.21	0.29
	CV	34.4	21.6	17.9	18.85	17.33	10.51	16.95	13.65	5.92	16.89	21.63	40.14
	CD	0.57	-	-	0.345	0.49	0.42		0.47	0.17	-	-	-
N	**SE(m)**	0.23	0.25	0.2	0.13	0.19	0.16	0.11	0.18	0.07	0.45	0.35	0.34
	CV	34.8	21.6	17.99	18.85	17.33	10.51	16.94	13.65	5.92	16.89	21.63	40.14
	CD	0.7	0.79	0.64	0.42	0.59	0.51	0.36	0.87	0.21	-	0.79	-
I X N	**SE(m)**	0.32	0.36	0.28	0.19	0.27	0.23	0.16	0.26	0.09	0.47	0.39	0.39
	CV	34.8	21.6	17.9	18.85	17.33	10.51	16.94	13.65	5.93	16.89	21.63	40.14
	CD	-	-	-	-	-	-	-	-	-	-	-	-
Fvalue	**I**	*	NS	NS	*	*	*	NS	*	**	NS	NS	NS
	N	**	**	*	**	**	**	**	**	**	NS	*	NS
	I X N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Where, V1 is Jyothi, V2- Jaya, V3- Uma, V4- Kanchana, I1 is waterlogged/ flooded, I2 is alternate wetting and drying (AWD), N1 is 0 % application of the recommended dose of nutrients, N2 is 100 % application of the recommended dose of nutrients through inorganic fertilizers and N3 is 120 % N of the recommended dose of nutrients through inorganic fertilizers. Significance at P< 0.05 * and P>0.01 **, LSD test.

With respect to the cultivar *Kanchana,* only in the panicle initiation stage, did nitrogen application treatments have a significant impact on LAI, and the rest were not significantly influenced. The flooded condition along with N3 nitrogen treatment had the highest values for LAI in the initial stage, i.e., 2.3±0.2. It was followed by the N1 treatment (1.9±0.3) and the N2 treatment (1.7±0.4), respectively. In the AWD condition also, the N3 treatment had the highest value for LAI in the initial stage, i.e., 2.3±0.8 and it was followed by the N2 treatment (1.7±0.2) and the N1 treatment (0.9±0.3). During the panicle initiation period (60th day after planting), the highest value of LAI for flooded conditions was observed for N3 treatment (3.8±0.5), which was followed by N2 (2.8±1.2) and N1 treatments (2.7±0.3), respectively. In the case of AWD condition, the highest LAI was observed for N3 treatment (3.4±0.9), and the least was observed in N2 & N1 treatment (2.4±0.5 & 2.4±0.8, respectively). Then during the maturity stage (105th day after planting), N3 treatment has the highest values for LAI, i.e., 3.1±1.1, which was followed by N2 treatment (2.5±0.8) and N1 treatment (1.9±0.8) for the flooded condition. In the AWD condition also, N3 treatment has the highest values for LAI in the maturity stage, i.e., 2.8±1.2. It was followed by N2 treatment (2.1±0.4) and N1 treatment (1.8±0.9), respectively.

Number of panicles

The number of panicles observed during the panicle initiation stage (60th day after planting) and maturation stage (105th day after planting) are tabulated in Table 4.5. The treatments on nutrient management significantly influenced the number of panicles in all four varieties of paddy tested in this experiment. In *Jyothi* rice variety, the N3 nitrogen treatment had the highest values for the number of panicles in both the flooded as well as the AWD treatments, i.e., 8.3±2.5 and 6.0±1.0 respectively and the least for N1 treatment (4.7±0.6 for the flooded and 4.3±1.2 for the AWD treatments) during the panicle initiation period. In the maturity stage also, N3 nitrogen treatment had the highest values for the number of panicles in the flooded and the AWD treatments, i.e., 8.0±2.0 and 6.0±1.0 respectively and the least was observed for N1 treatment (4.7±0.6 for flooded and 3.0±0.0 for AWD).

In the case of *Jaya* variety, both the irrigation and nutrient management practices had a statistically significant effect on the number of panicles. The N3 treatment had the highest values for the number of panicles in the flooded treatment and the AWD treatment, i.e., 8.0±0.5 and 5.0±1.0 respectively. It was followed by the N2 treatment (5.3±1.2 for the

flooded and 4.5±1.8 for the AWD treatments) and the least was noticed for the N1 treatment (4.0±1.0 for the flooded and 3.3±1.0 for the AWD treatments) during the panicle initiation stage. In the maturity stage also, the N3 treatment recorded the highest values for the number of panicles in the flooded treatment and the AWD treatment, i.e., 6.7±0.3 and 5.3±0.6 respectively. It was followed by the N2 treatment (5.3±1.2 for the flooded and 4.0±1.0 for the AWD treatments) and the least was noticed in the N1 treatment (4.3±1.6 for the flooded and 3.3±0.6 for the AWD treatments).

In the *Uma* paddy variety, nutrient treatments significantly influenced the panicle production whereas the water management had little effect. But this variety showed a significant effect on panicle production through the combined interaction between the treatments. In both the irrigation conditions, N3 treatment has the highest values for the number of panicles i.e., 10.7±1.5 and 8.0±1.0, respectively, and the least for N1 treatment (4.0±1 for flooded and 5.3±1.5 for AWD) during the panicle initiation stage. In the maturity stage also, N3 treatment had the highest values for the number of panicles in the flooded treatment and the AWD treatment, i.e., 10.3±1.6 and 8.0±0.0 respectively, followed by the N2 treatment (5.7±0.6 for the flooded irrigation and 6.3±0.6 for the AWD irrigation) and the least for N1 treatment (5.3±0.6 for flooded and 4.3±0.6 for AWD). So, among the treatments, I1N3 was the superior treatment and I1N1 was the inferior treatment, and this variety showed a statistically significant effect on the interaction.

In the case of *Kanchana* variety, the nitrogen treatments have a significant effect during both the panicle initiation stage and the maturity stage, whereas, in the irrigation management treatments, only the maturity stage had a significant effect on the number of panicles. Also, it failed to exert any interaction effect on the number of panicles in this experiment. The N3 treatment has the highest values for the number of panicles in the flooded and the AWD treatments, i.e., 5.0±1.7 and 4.3±1.2, respectively. It was followed by N2 treatment (3.7±0.6 for the flooded and 3.0±0.0 for the AWD treatments) and the least for N1 treatment (3.3±1.2 for the flooded and 2.3±0.6 for the AWD treatments) during the panicle initiation stage. In the maturity stage also, the N3 treatment had the highest values for the number of panicles in the flooded treatment as well as the AWD treatment, i.e., 5.3±0.6 and 4.7±0.6, respectively. It was followed by the N2 treatment (4.7±0.6 for the flooded and 3.0±0.0 for the AWD treatments) and the least for the N1 treatment (3.7±0.6 for the flooded and 3.0±1.0 for the AWD treatments).

Table 4.5. Number of panicles of four different rice varieties, are represented as Mean ± Standard Deviation (SD) of three replications.

		V1		V2		V3		V4	
Treatment		**60 DAT**	**105DAT**	**60 DAT**	**105DAT**	**60 DAT**	**105DAT**	**60 DAT**	**105DAT**
	I1N1	4.7±0.6	4.7±0.6	4.0±1.0	4.3±0.6	4.0±1.0^{d}	4.3±0.6^{e}	3.3±1.2	3.7±0.6
	I1N2	6.7±0.6	6.3±0.6	5.3±1.2	5.3±1.2	6.7±0.6^{c}	5.7±0.6^{cd}	3.7±0.6	4.7±0.6
	I1N3	8.3±2.5	8.0±2.0	8.0±0.5	6.7±0.3	10.7±1.5^{a}	10.33±0.6^{a}	5.0±1.7	5.3±0.6
	I2N1	4.3±1.2	3.0±0.0	3.0±1.0	3.3±0.6	5.3±1.5^{cd}	5.3±0.6^{d}	2.3±0.6	3.0±1.0
	I2N2	5.0±1.7	4.3±1.2	4.5±1.8	4.0±1.0	6.7±0.6^{c}	6.3±0.6^{c}	3.0±0.0	3.0±0.0
	I2N3	6.0±1.0	6.0±1.0	5.0±1.0	5.3±0.6	8.0±1.0^{b}	8.0±0.0^{b}	4.3±1.2	4.7±0.6
I	**SE(m)**	0.49	0.36	0.37	0.279	0.36	0.15	0.34	0.23
	CV	24.58	20.04	22.61	16.3	15.83	6.71	28.45	16.02
	CD	-	1.11	1.16	0.88	-	-	-	0.68
N	**SE(m)**	0.47	0.44	0.45	0.34	0.45	0.18	0.42	0.27
	CV	24.58	20.04	22.61	16.73	15.83	6.71	28.45	16.02
	CD	1.8	1.36	1.42	1.08	1.4	0.81	1.29	0.84
I X N	**SE(m)**	0.83	0.62	0.64	0.48	0.63	0.26	0.59	0.38
	CV	24.58	20.04	22.61	16.73	15.83	6.71	28.45	16.02
	CD	-	-	-	-	1.98	0.81	-	-
Fvalue	**I**	NS	**	**	**	NS	NS	NS	**
	N	**	**	**	**	**	**	*	**
	I X N	NS	NS	NS	NS	*	**	NS	NS

Where, V1 is *Jyothi*, V2- *Jaya*, V3- *Uma*, V4- *Kanchana*, I1 is waterlogged/ flooded, I2 is alternate wetting and drying (AWD), N1 is 0 % application of the recommended dose of nutrients, N2 is 100 % application of the recommended dose of nutrients (RDN) through inorganic fertilizers and N3 is 120 % N of the RDN through inorganic fertilizers. Significance at P< 0.05 * and P>0.01 **, LSD test.

4.1.4. Water input saving

The total water requirement for the *Mundakkan* (Rabi) season for the continuous flooded paddy cultivation was 1786.1 mm whereas for the alternating wetting and drying (AWD) cultivation, the total water requirement was 1115.8 mm, respectively. The detailed irrigation schedule is given in Table 4.6. The results showed that, during the growing period, rainfall had a substantial impact on daily water input use. It showed that if there is rain and the soil moisture is maintained, it results in a reduction in irrigation water demand. There is no need for further irrigation when there has been adequate rainfall and the land has acquired moisture from the rain. This can result in less overall water input on rainy days. During the initial stages, i.e., nursery and land preparation, a total of 442 mm was used for both flooded and AWD treatments. Whereas during the initial stage of rice growth, 388.6 mm was used in flooded treatment and 380.8 mm was used in AWD treatment. The developmental stage of flooded treatment required 299.4 mm of water, and AWD treatment required only 55.2 mm of water during the same period. The maturity stage of rice in this experiment required 396.0 mm of water for flooded treatment and 114.9 mm of water for AWD treatment. Then before harvest 260.1 mm of water was used in flooded treatment and mm of water was used in AWD treatment. Hence, 37.52 % of water input was saved in this experiment.

Table 4.6. Detailed irrigation schedule of flooded and AWD irrigation

Months	Stage	Flood mm/dec	AWD mm/dec
August	Nursery	50	50
August	Nursery/ Land Preparations	150	150
September	Nursery/ Land Preparations	242	242
September	Initial	292	365.9
September	Initial	96.6	15.5
October	Developmental	100.6	2.9
October	Developmental	98.3	31.7
October	Developmental	100.5	20.6
November	Middle	91.2	37.2
November	Middle	101.2	34.2
November	Middle	101.7	0.2
December	Middle	101.9	43.3
December	Late	92.7	40.9
December	Late	87.3	47.8
January	Late	74.1	33.4
January	Late	6	0.2
Total		1786.1	1115.8

4.2. Experiment -2

The results acquired from the research work entitled "*Evaluation of nutrient management and method of planting on crop productivity of aerobic rice and estimating the water saving in aerobic using FAO-CROPWAT model"* were collected and elucidated in this chapter. The results from the first experiment showed that alternate wetting and drying results in savings of water. Hence, the second experiment was conducted with respect to assessing the management practices for aerobic rice. This experiment was conducted to evaluate different nutrient management practices and methods of planting to aerobic rice production in addition an attempt was made to quantify the water saving under aerobic rice and the results obtained from this experiment are detailed hereunder.

4.2.1. Experimental soil and site characteristics

Table 4.7 presents the tabulated results of soil physico- chemical parameters for the experimental plot. Overall, the soil at the experimental site exhibits a sandy clay loam texture, with a bulk density of 1.01 g cc^{-1} and a particle density of 2.06 g cc^{-1}. Taxonomically, it falls under the Kunnamangalam series, classified by the USDA as *Mixed; Isohyperthermic, Typic Kanhaplustults*, and is characterized as lateritic in nature. The soil is having an acidity with a pH of 5.93. The organic carbon content is measured at 1.02 %, while available nitrogen is relatively low at 255 kg ha^{-1}. In terms of nutrient availability, the soil is classified as medium in available phosphorus (20.31 kg ha^{-1}) and medium in available potassium (130.6 kg ha^{-1}), respectively. The field capacity and wilting point of the soils are recorded at 24.12 % and 15.26 %, respectively.

Table 4.7. Soil physical and chemical parameters of experimental plot

Soil parameters	Values
Bulk density (g cc^{-1})	1.01
Particle density (g cc^{-1})	2.06
pH	5.93
Organic carbon-OC (%)	1.02
Soil Available N (kg ha^{-1})	255
Soil Available P (kg ha^{-1})	20.31
Soil Available K (kg ha^{-1})	130.6
Field capacity (%)	24.12
Wilting point (%)	15.26

4.2.2. Climatic parameters

The experimental site experiences a humid tropical climate featuring hot, dry summers and winter cold seasons. The total annual rainfall for the year was 3351.6 mm, with approximately 80 % of this precipitation occurred during the southwest monsoon season, spanning from May to September. Throughout the entire crop period, the cumulative rainfall reached 2092.8 mm. The average maximum temperature experienced

in experimental location during the crop period was 37.5 ^{0}C and average minimum temperature prevailed during the experimental period was 20.0 ^{0}C. Average maximum relative humidity and minimum relative humidity were found 98.0 % and 72.0 % respectively during the experimental period (Fig.4.2).

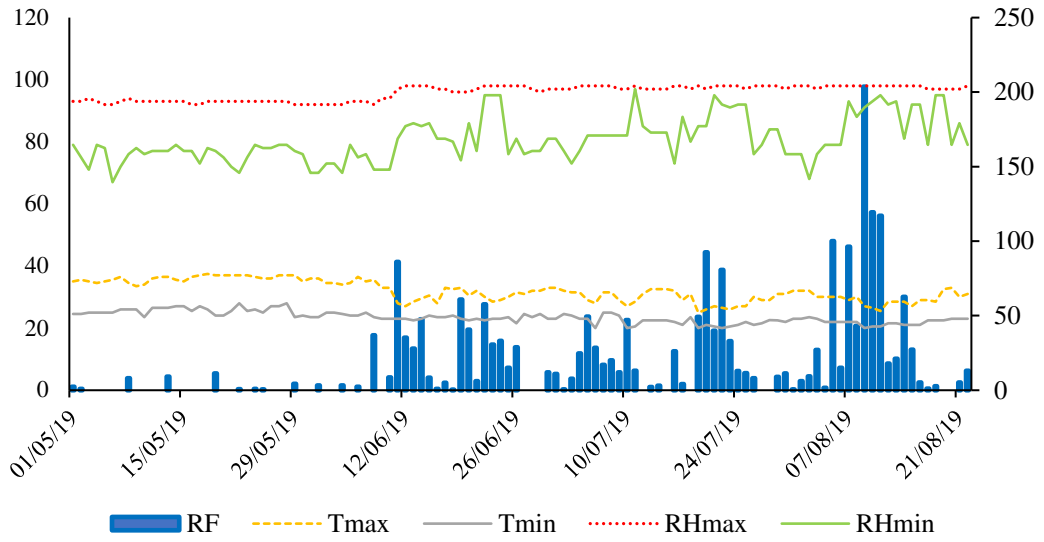


Fig.4.2. Weather data during crop growth period- Experimental 2

4.2.3. Biometric characteristics

Plant biometrics represents a study of the development of plants. The crop biometric/ morphological characteristics measured are height of the plant in cm and tiller numbers during the four different crop developmental stages under different treatments are summarized in Table 4.8.

Plant height

The observed plant heights of different varieties are represented in Table 4.8. The results indicated that aerobic rice exhibited statistically significant differences among the various treatments applied. Direct-seeded rice (DSR) plants showed higher values for plant height than transplanted ones and with respect to nutrient treatment, the T1 (125 % of inorganic fertilizers) had the highest plant height followed by the T2 treatment (100 % of inorganic fertilizers) and the lowest value was observed in T3 treatment (100 % of organic manures) in both the directly planted and the transplanted plants, i.e. when the nitrogen level was increased resulted in increased plant's height significantly.

In the DSR method, plants with T3 treatment had the highest values for plant height in the initial stage, i.e., 36.2±1.3 cm. It was followed by the T2 treatment (34.4±1.1 cm)

and the T1 treatment (25.4±1.3 cm), respectively. In the transplanted condition also, T3 treatment had the highest values for plant height in the initial stage, i.e., 31.8±1.3 cm. It was followed by the T2 treatment (26.4±1.3 cm) and the T1 treatment (21.2±1.9 cm), respectively. The P1T3 treatment was statistically on par with the P2T2 treatment during the initial stage. After fifty days of planting, the plant height increased to 76.6±12.1 cm, 69.6±1.1 cm and 54.2±2.9 cm for treatments T1, T2, and T3 in DSR, respectively, compared to 66.5±2.8 cm, 60.0±2.5 cm, and 51.0±3.1 cm for the transplanted rice plants for the same treatments. During this period, P1T1 was found to be a statistically superior treatment followed by the P1N2 treatment and P2T1 treatment. The least was noticed in the P2T1 treatment followed by the P2T2 treatment. The P1T3 and P2T3 treatments were statistically on par and at the same time inferior to the other treatment. Then, at the eighty-five days of planting, the plant height increased to 85.0±2.2 cm, 77.6±1.3 cm and 66.0±2.3 cm for treatments T1, T2, and T3 in DSR, respectively, compared to 75.1±0.9 cm, 73.8±1.0 cm, and 64.4±2.2 cm for the transplanted rice plants for the same treatments. Then during the last sampling (i.e., on the 115th day) also, the P1T1 treatment had the highest values for plant height i.e., 87.5±1.9 cm and the least for the P2T3 treatment (64.6±2.3 cm). In the observations from the 85th day and 115th day, each treatment significantly differs from the other and among them, P1T1 was the superior treatment and P2T3 was the inferior treatment. Also, a significant combined influence was observed for all stages of methods of planting and nutrient application on plant height.

Number of tillers

The results indicated that the aerobic rice exhibited significant differences statistically among the various treatments applied (Table 4.8). According to the results, the number of tillers was maximum with T1 treatment, followed by T2 and the lowest values were observed in T3 treatment in both directly planted and transplanted rice. The number of tillers on the 30th day, for the DSR treatment was 13.0±1.5, 11.0±1.8, and 8.0±0.7 for treatments T1, T2, and T3, compared to 8.2±0.8, 7.0±1.2, and 6.0±1.2 for the transplanted treatments T1, T2, and T3, respectively. After the 50th day of planting, the number of tillers increased to 17.0±1.0, 15.2±0.5, and 11.8±0.5 for the T1, T2, and T3 treatments in DSR, respectively, whereas the transplanted rice showed the tillers as 14.0±0.9, 12.0±1.4 and

Table 4.8. Growth characteristics such as number of tillers and height of rice plant *cv. Uma*, are represented as Mean ± Standard Deviation (SD) of six replications.

METHOD	TREATMENT	30th Day		50th Day		85th Day		115th Day	
		Number of tillers	Height of plant (cm)	Number of tillers	Height of plant (cm)	Number of tillers	Height of plant (cm)	Number of tillers	Height of plant (cm)
P1	T1	13.0±1.5^{a}	36.2±1.3^{a}	17.0±1.0^{a}	76.6±12.1^{a}	19.4±0.5^{a}	85.0±2.2^{a}	19.4±1.1^{a}	87.5±1.9^{a}
	T2	11.0±1.8^{b}	34.4±1.1^{ab}	15.2±0.5^{b}	69.6±1.1^{b}	17.2±2.8^{ab}	77.6±1.3^{b}	17.0±1.1^{b}	82.5±2.6^{b}
	T3	8.0±0.7^{cd}	25.4±1.3^{c}	11.8±0.5^{ed}	54.2±2.9^{e}	14.4±0.5^{c}	66.0±2.3^{e}	14.0±0.2^{d}	67.1±1.7^{e}
P2	T1	8.2±0.8^{c}	31.8±1.3^{b}	14.0±0.9^{c}	66.5±2.8^{c}	17.0±1.0^{ab}	75.1±0.9^{c}	16.8±0.5^{c}	76.1±1.9^{c}
	T2	7.0±1.2^{d}	26.4±1.3^{c}	12.0±1.4^{d}	60.0±2.5^{d}	16.0±0.5^{b}	73.8±1.0^{d}	15.4±1.0^{c}	72.9±1.8^{d}
	T3	6.0±1.2^{e}	21.2±1.9^{d}	10.8±0.5^{e}	51.0±3.1^{e}	12.4±3.9^{cd}	64.4±2.2^{f}	12.2±0.6^{e}	64.6±2.3^{f}
P	**SE(m)**	0.20	0.80	0.18	0.87	0.81	0.15	0.08	0.18
	CV	9.92	8.06	5.03	8.51	13.19	1.53	3.42	0.74
	CD	0.60	2.2	0.53	3.82	1.08	0.56	0.30	0.62
T	**SE(m)**	0.25	0.85	0.22	0.95	0.86	0.26	0.21	0.21
	CV	9.92	8.06	5.03	8.51	13.19	1.53	3.42	0.74
	CD	0.74	4.4	0.65	4.85	1.78	0.75	0.35	0.65
P X T	**SE(m)**	0.39	1.07	0.30	2.37	0.96	0.50	0.24	0.25
	CV	9.92	8.06	5.03	8.51	13.19	1.53	3.42	0.74
	CD	1.14	3.14	0.89	6.99	2.09	1.48	0.72	0.74
F value	**P**	**	**	**	**	**	**	**	**
	T	**	**	**	**	*	*	**	*
	P X T	**	**	**	**	*	**	**	**

Where, P1- DSR, P2- Transplanted, T1 is 125 % of inorganic fertilizers, T2 is 100 % of inorganic fertilizers and T3 is 100 % of organic manures. a, b, c, d, e, and f in columns means treatments with same letter do not differ significantly (P< 0.05) * and (P>0.01) **, LSD test. SEM: Standard Errors of Mean; CD: Critical difference; CV: Coefficient of variance.

10.8±0.5 for T1, T2, and T3 treatments, respectively. In both stages, among the treatments, P1T1 was found to be superior treatment and P2T3 was found to be the inferior treatment. The next observation was made on the 85th day, and the highest number of tillers observed for DSR was 19.4±0.5 for treatment T1, and the lowest was 14.4±0.5 for T3, compared to 17.0±1.0 and, 12.4±3.9 for transplanted treatments T1 and T3, respectively. Here, treatments P1T2 and P2T1 were statistically on par with each other. The last sampling was taken on the 115th day after planting and the highest number of tillers for DSR was 19.4±1.1 for treatment T1, followed by 17.0±1.1 for T2 treatment and the lowest was 14.0±0.2 for T3. The highest number of tillers for transplanted rice was for T1 treatment at 16.8±0.5, followed by T2 treatment at 15.4±1.0 and the least was 12.2±0.6 for T1 treatment, respectively. In the observations from the 115th day, each treatment significantly differs from the others and among them, P1T1 was the superior treatment and P2T3 was the inferior treatment. Similarly, to plant height, in the case of tillers also, the results exhibited a positive effect on the interaction effect of the method of planting and application of nutrients and it was found to be statistically significant.

4.2.4. Yield

Results on the crop yield showed a significant difference among the nutrient management and methods of planting treatments (Table 4.9). The impacts of different fertilizer treatments on the crop yield are statistically analysed using two-way ANOVA. The least significant differences (LSD) test was used to determine the significance of differences in yields. The average value of five replicates was used for further analysis in the LSD test.

The results exhibited that application of 125 % of N (based on the recommended dose) through inorganic fertilizers (T1) resulted in the higher yield of 4851.8±74.7 kg ha^{-1} in DSR and 3714.1±103.2 kg ha^{-1} in the transplanted and it was statistically superior over the other treatments**.** This was followed with T2 treatment, which recorded a yield of 4307.2±123.9 kg ha^{-1} for DSR treatments and 3215.8±138.9 kg ha^{-1} for the transplanted rice treatments. The organic manure applied treatment (T1) resulted in poor performance in yield (2435.0±108.8 kg ha^{-1} in DSR and 1287.2±169.8 kg ha^{-1} in transplanted) and it was statistically inferior to the other treatments. Likewise, among the planting methods, the Direct Seeded Rice (DSR) treatment outperformed the transplanting treatment and demonstrated statistical significance.

Table 4.9. Yield of rice plant *cv. Uma* are represented as Mean ± Standard Deviation (SD) of six replications.

		Direct sown rice (kg ha^{-1})	Transplanted rice (kg ha^{-1})
T1		4851.8±74.7^{a}	3714.1±103.2^{a}
T2		4307.2±123.9^{b}	3215.8±138.9^{b}
T3		2435.0±108.8^{c}	1287.2±169.8^{c}
P	**SE(m)**	43.05	
	CV	5.05	
	CD	127.01	
T	**SE(m)**	52.73	
	CV	5.05	
	CD	155.56	
P X T	**SE(m)**	74.57	
	CV	5.05	
	CD	-	
F value	**P**	**	
	T	**	
	P X T	-	

Where, T1 is 125 % of RDF through inorganic fertilizers, T2 is 100 % of RDF through inorganic fertilizers and T3 is 100 % of RDF through organic manures)

4.2.5. Water Saving

The CROPWAT model was employed to calculate the total crop water requirement and net irrigation requirement for all three rice-growing seasons in Kerala, considering both aerobic and anaerobic rice cultivation methods (refer to Table 4.10). For the *Viruppu* (Kharif), *Mundakkan* (Rabi), and *Puncha* (summer) seasons, the total water requirement for anaerobic cultivation stood at 1589.9 mm, 1607.2 mm, and 1705.6 mm, respectively (Sruthi and Surendran, 2023). In contrast, for aerobic cultivation, the corresponding total water requirement was 969.9 mm, 987.2 mm, and 1085.6 mm. The net irrigation requirement (NIR) for aerobic rice was determined to be 286.6 mm, 650.4 mm, and 962.0 mm during the *Viruppu*, *Mundakkan*, and *Puncha* seasons, respectively. In the case of anaerobic rice, the NIR values were 802.3 mm, 1607.2 mm, and 1582.0 mm for the

Viruppu, Mundakan, and Puncha seasons, respectively. To project water savings in the Kozhikode district, the Puncha (summer) season was specifically considered for calculating water savings. This choice was made because the third season crops are predominantly irrigated in Kerala, potentially resulting in higher water savings. Simulations indicated water savings ranging from 54.72 mm to 547.21 mm for 10 % to 100 % of the total rice-cultivated areas in Kozhikode district. The water savings for aerobic and flooded rice are graphically represented in Fig. 4.3, demonstrating a substantial water saving of 36.4 % in the case of aerobic rice compared to flooded rice.

Table 4.10. Irrigation requirement output for *Viruppu* (A), *Mundakan* (B), and *Puncha* (C) rice seasons using CROPWAT model for the experiment in comparison to the anaerobic rice.

***Viruppu* Season**

	Anaerobic rice			**Aerobic rice**		
Stage	**ET_C mm/dec**	**ER mm/dec**	**IR mm/dec**	**ET_C mm/dec**	**ER mm/dec**	**IR mm/dec**
Nurs	0.5	1.4	0	0.5	1.4	0
Nurs/ LPr	9.9	18.7	0	9.9	18.7	0
Nurs/ LPr	47.9	28	19.9	47.9	28	19.9
Init	106.6	38.3	68.3	66.6	38.3	28.3
Init	106.5	47.3	59.2	66.5	47.3	19.2
Deve	106.3	54.5	51.8	66.3	54.5	11.8
Deve	96.9	63.9	33	56.9	63.9	0
Deve	91.9	72.4	19.5	51.9	72.4	0
Deve	91.2	70.3	20.9	51.2	70.3	0
Mid	90.9	67.5	23.4	50.9	67.5	0
Mid	90.1	66.8	23.3	50.1	66.8	0
Mid	94.1	63.7	30.4	54.1	63.7	0
Late	91.8	60.2	31.6	51.8	60.2	0
Late	91.5	57.3	34.2	51.5	57.3	0
Late	94.7	55.3	39.4	54.7	55.3	0
Late	79.1	31.7	47.4	39.1	31.7	7.4
Total	1289.9		502.3	769.9		86.6
Land preparation	300		300	200		200
Total water requirement	**1589.9**		802.3	**969.9**		286.6

B. Mundakan Season

Stage	Anaerobic rice			Aerobic rice		
	ET_C mm/dec	**ER mm/dec**	**IR mm/dec**	**ET_C mm/dec**	**ER mm/dec**	**IR mm/dec**
Nurs	0.4	5.3	0	0.4	5.3	0
Nurs/ LPr	7.6	50.4	0	7.6	50.4	0
Nurs/ LPr	37.3	50.7	0	37.3	50.7	0
Init	96.8	52.7	44.1	56.8	52.7	4.1
Init	97.3	53.4	43.9	57.3	53.4	3.9
Deve	100.5	47.7	52.8	60.5	47.7	12.8
Deve	96.6	42.4	54.2	56.6	42.4	14.2
Deve	96.4	38	58.4	56.4	38	18.4
Deve	96.7	28.2	68.5	56.7	28.2	28.5
Mid	96.9	16.1	80.8	56.9	16.1	40.8
Mid	97	6	91	57	6	51
Mid	101.7	4.3	97.4	61.7	4.3	57.4
Late	98.7	2.3	96.4	58.7	2.3	56.4
Late	98.3	0	98.3	58.3	0	58.3
Late	102	0.2	101.8	62	0.2	61.8
Late	83	0.2	82.8	43	0.2	42.8
Total	1307.2		970.4	787.2		450.4
Land preparation	300		300	200		200
Total water requirement	**1607.2**		1270.4	**987.2**		650.4

B. Puncha Season

Stage	Anaerobic rice			Aerobic rice		
	ET_C mm/dec	**ER mm/dec**	**IR mm/dec**	**ET_C mm/dec**	**ER mm/dec**	**IR mm/dec**
Nurs	3.9	6.0	0.0	3.9	6.0	0.0
Nurs/ LPr	39.5	4.3	35.2	39.5	4.3	35.2
Init	96.9	2.3	94.6	56.9	2.3	54.6
Init	98.9	0.0	98.9	58.9	0.0	58.9
Deve	104.8	0.2	104.6	64.8	0.2	64.6
Deve	102.6	0.3	102.3	62.6	0.3	62.3
Deve	104.6	0.1	104.5	64.6	0.1	64.5
Deve	97.0	1.8	95.2	57.0	1.8	55.2

Mid	107.8	2.6	105.2	67.8	2.6	65.2
Mid	109.3	3.6	105.7	69.3	3.6	65.7
Mid	115.1	9.2	105.9	75.1	9.2	65.9
Late	110.8	14.1	96.7	70.8	14.1	56.7
Late	110.0	18.7	91.3	70.0	18.7	51.3
Late	106.1	28.0	78.1	66.1	28.0	38.1
Late	98.3	34.5	63.8	58.3	34.5	23.8
Total	1405.6		1282.0	885.6		762.0
Land preparation	300.0		300.0	200.0		200.0
Total water requirement	**1705.6**		1582.0	**1085.6**		962.0

(ET_C – Crop evapotranspiration, ER– Effective Rain fall, IR – Irrigation Requirement, Nurs – Nursery phase of rice cycle, LPr – Land preparation phase, Init – Initial phase, Deve- Developmental phase, Mod- Middle Phase, Late- Late phase)**.**

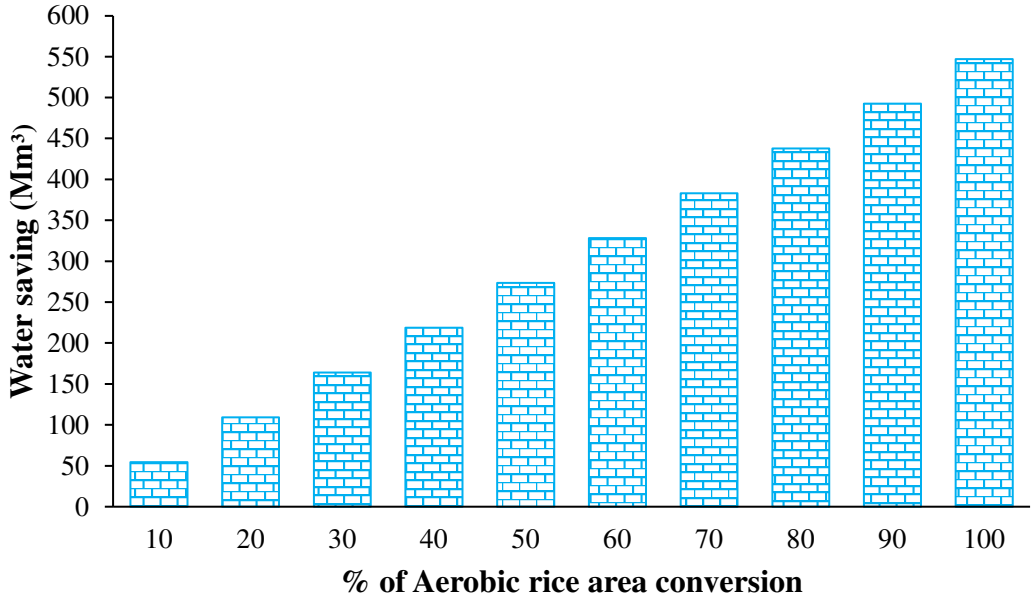


Fig.4.3. Irrigational water savings from converting different percentage of areas of flood cultivation to aerobic cultivation.

4.3. Experiment -3

The results acquired from the research work entitled "*Assessing the different levels of water and nutrient application on growth and productivity of rice under aerobic cultivation"* were elucidated hereunder. This experiment was designed to assess the effect of different levels of water and nutrient management practices with aerobic rice in yield.

During the field experiment, leaf rolling phenomenon was observed in some patches of the experimental plot irrespective of the treatments carried out. Hence, study was conducted to understand the leaf rolling behaviour and how that can be manged with the help of different moisture absorbing mediums in upland rice cultivation was evaluated.

4.3.1. Experimental soil and site characteristics

Tabulated results for the soil's physical and chemical parameters from the experimental plot are presented in Table 4.11 The soil exhibits a sandy clay loam texture, characterized by a bulk density of 1.1 g cc^{-1} and a particle density of 2.18 g cc^{-1}. Taxonomically, the soil belongs to the Kunnamangalam series under the USDA class of *Mixed; Isohyperthermic, Typic Kanhaplustults*, and is charactrized as lateritic in nature. The soil's pH was 6.75, with an organic carbon content of 1.72 % and an available nitrogen (N) content of 205 kg ha^{-1}. The available phosphorus (P) content of the experimental soil falls within a medium range, measuring 19.61 kg ha^{-1}, while the available potassium (K) content is also medium, with a value of 110.8 kg $ha^{-1.}$ Field capacity and wilting point of the soils are found to be 22.42 % and 13.54 %, respectively.

Table 4.11. soil physical and chemical parameters of experimental plot

Soil parameters	Values
Bulk density (g cc^{-1})	1.1
Particle density (g cc^{-1})	2.18
pH	6.75
Organic carbon (%)	1.72
Available N (kg ha^{-1})	205
Available P (kg ha^{-1})	19.61
Available K (kg ha^{-1})	110.8
Field capacity (%)	22.42
Wilting point (%)	13.54

4.3.2. Climatic parameters

The experimental field site experiences a humid tropical climate characterized by scorching, dry summers and chill winter seasons. The region falls under the climate of

humid tropical with average annual precipitation of 3085 mm. Details about the observed weather parameters were given in Fig.4.4. The maximum temperature experienced in experimental location during the crop period was 40.7 ^{0}C and minimum temperature prevailed during the experimental period was 19.0 ^{0}C. Throughout the crop period total rainfall received was 105.0 mm. Average maximum relative humidity and minimum relative humidity was found 97.0 % and 50.0 % respectively during the experimental period.

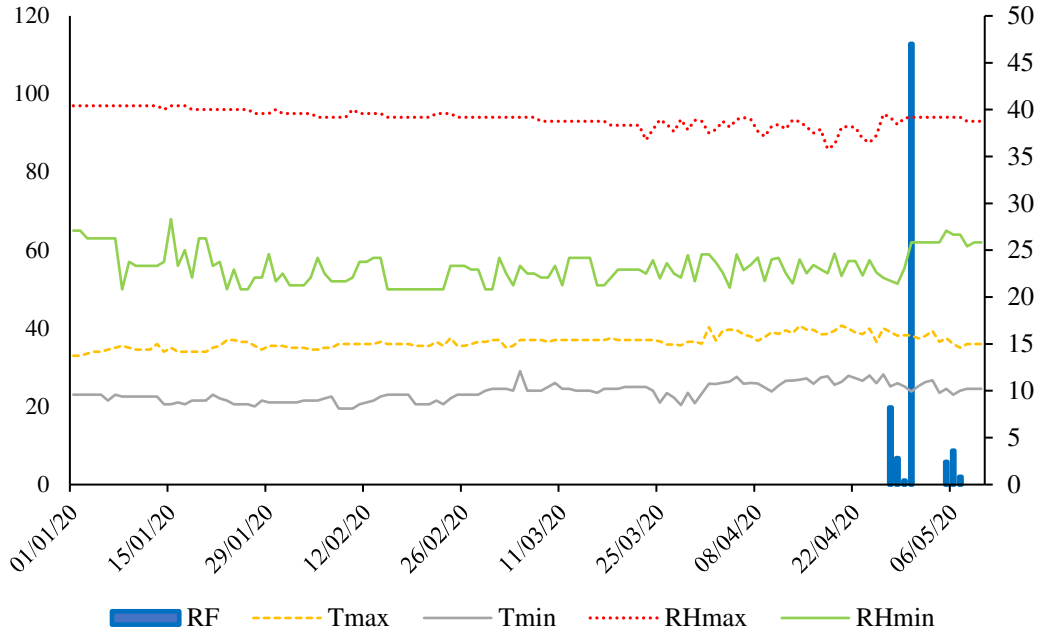


Fig. 4.4. weather data during crop growth period- Experimental 3

Initial experiment

4.3.3. Plant characteristics

Plant biometric represents a study of the development of plants. The rice growth characteristics measured were height of the plant and number of tillers and photosynthetic rate during initial and final crop development stages under different treatments and are summarized in Table 4.12.

Plant height

The observed plant height of *Uma* cultivar is represented in Table 4.12. Results showed statistically significant differences among the different treatments attempted. The water management treatments have a significant effect in plant height during both the initial and the final stages. However, in the case of nutrient management treatment, only

the final stage was significantly influenced. I2T3 treatment showed higher values for plant height in both the initial and the final stages (41.0±2.4 cm and 83.5±5.4 cm) and it was followed by I1T3 treatment (38.8±4.9 cm and 79.7±4.8 cm), and I2T2 treatment (38.6±4.1 cm and 71.7±5.0 cm), respectively. The lowest value for the plant height was observed for I1T1 treatment (32.8±2.2 cm and 56.6±4.8 cm) in both the initial and the final stages of rice development, respectively. The interaction effect was non-significant i.e. combined effects were absent in both the initial and the final stages of plant height in this experiment.

Number of tillers

The results (Table 4.12) showed that aerobic rice cultivation had a significant effect among the different treatments attempted. Nutrient management treatments had significant effects during both the initial and the final stages but, irrigation treatment could only affect the initial stages of rice. Also, the combined effect of both irrigation and nutrient treatments failed to significantly influence the number of tillers. During the initial stage, the least number of tillers were found in the I1T1 treatment (6.0±0.0) and the highest was found in the I2T3 treatment (8.0±0.7). During the final stage, the highest number of tillers were found in the I2T3 treatment the (12.8±1.3), followed by I1T3 treatment the (11.6±0.9), and the I2T2 treatment (10.8±0.8). The least number of tillers during the final stage was sound in the I1T1 treatment (8.2±1.3), followed by the I2T1 treatment (9.2±0.8), and the I1N2 treatment (10.6±0.6).

Photosynthesis rate

The results (Table 4.12) showed that; only nutrient management treatments had a significant effect on the photosynthetic rate. During the initial stage, the highest value for photosynthetic rate was found in I2T3 (29.1±2.6 µmol $m^{-2}s^{-1}$), followed by I1T3 (27.1±1.9 µmol $m^{-2}s^{-1}$), I2T2 (25.3±3.3 µmol $m^{-2}s^{-1}$), I2T1 (23.3±1.4 µmol $m^{-2}s^{-1}$), I1T2 (22.4±2.9 4 µmol $m^{-2}s^{-1}$), and least for I1T1 treatment (20.5±3.3 µmol $m^{-2}s^{-1}$). In the last stage, the highest photosynthetic rate was shown by both I2T3 (17.5±1.3 µmol $m^{-2}s^{-1}$) and I1T3 treatments (12.7±2.6 µmol $m^{-2}s^{-1}$) and the lowest was measured in I2T1 treatment (9.1±1.3 µmol $m^{-2}s^{-1}$).

Table 4.12. Growth characteristics such as number of tillers, plant height, and photosynthetic rate, is represented as Mean ± Standard Deviation (SD) of five replications.

Treatment		Initial			Final		
		No. of tillers	Plant height (cm)	Photosynthesis rate (µmol $m^{-2}s^{-1}$)	No. of tillers	Plant height (cm)	Photosynthesis rate (µmol $m^{-2}s^{-1}$)
I1T1		6.0±0.0	32.8±2.2	20.5±3.3	8.2±1.3	56.6±4.8	9.7±1.3
I1T2		6.8±0.5	36.6±4.6	22.4±2.9	10.6±0.6	68.4±6.1	12.7±2.6
I1T3		7.4±0.9	38.8±4.9	27.1±1.9	11.6±0.9	79.7±4.8	17.5±1.3
I2T1		7.2±0.5	38.6±6.1	23.3±1.4	9.2±0.8	64.9±3.8	9.1±1.7
I2T2		7.2±0.5	38.6±4.1	25.3±3.3	10.8±0.8	71.7±5.0	13.5±1.1
I2T3		8.0±0.7	41.0±2.4	29.1±2.6	12.8±1.3	83.5±5.4	17.5±1.3
	SE(m)	0.15	1.04	0.73	0.27	1.23	0.31
I	**CV**	8.17	10.71	11.56	10.06	6.74	9.03
	CD	0.44	3.08	-	-	3.63	-
	SE(m)	0.18	1.277	0.89	0.34	1.51	0.38
T	**CV**	8.17	10.71	11.56	10.06	6.74	9.03
	CD	0.54	-	2.65	0.98	4.45	1.12
	SE(m)	0.26	1.81	1.27	0.47	2.13	0.54
I X T	**CV**	8.17	10.71	11.56	10.06	6.74	9.03
	CD	-	-	-	-	-	-
	I	**	*	NS	NS	**	NS
Fvalue	**T**	**	NS	**	*	*	**
	I X T	NS	NS	NS	NS	NS	NS

Where, I1- 100 % ET_C , I2 – 120 % ET_C , T1- 75 % N- application of inorganic fertilizers, T2- 100 % N application of inorganic fertilizers, T3- 125 % N application of inorganic fertilizer (P< 0.05) *, (P< 0.01) **, LSD test. SEM: Standard Errors of Mean; CD: Critical difference; CV: Coefficient of variance.

4.3.4. Yield characteristics

Yield parameters like number of panicles/ tillers, length of panicle/ tiller, number of spikelest/ panicles, number of hollow spikelets/ panicle, number of grains in one panicle, number of filled grains, weight of thousand grains (WTG), harvest index and yield recorded at harvest were represented in Table 4.13, and analysed for statistical significance.

Number of panicles/ tills

Regardless of the treatments attempted during the experiment, the number of panicles per tiller (Table 4.13) showed that various nutrient management techniques had a significant effect. However, the water management treatments failed to affect significantly. Regarding nutrient management, the findings demonstrated that changing nutrient management had a substantial impact on the number of panicles per tiller on aerobic rice. The I2T3 was found to produce the highest number of panicles per tiller (15.2±3.9) compared to other treatments, which was followed by I1T3 treatment (12.8±3.9) and I2T2 treatment (12.2±4.9), The I1T1 treatment, which the least amount of nitrogen and water administered treatment, had the lowest number of panicles per tiller (6.2±1.3) followed by I2T1 treatment (7.4±3.1) and I1T2 treatment (11.0±2.2). The results from the experiment confirmed that that the interaction effect of irrigation and nutrient management was non-significant in number of panicles.

Length of panicle

The results of a statistical analysis of the data (Table 4.13) showed that differing nutrient management had a considerable impact on panicle length. The length of the panicle was significantly increased by increasing levels of N in terms of nutrient management. However, the water management treatments failed to affect significantly. The findings also demonstrated that interactions between water and nutrient management had significantly affected the length of the panicle under aerobic rice. The I2T3 treatment was found to produce the longest panicles per tiller (20.5±0.9 cm) compared to other treatments, which was followed by I1T1 treatment (18.7±1.7 cm) and I1T2 treatment (18.6±3.2 cm). The I2T2 treatment had the smallest panicles per tiller i.e., 14.7±0.9 cm, followed by I2T2 treatment (17.7±1.6 cm) and I1T3 treatment (17.9±2.4 cm).

Number of spikelets/ panicle

Statistical analysis of the data (Table 4.13) indicated that throughout the experiment, the number of spikelets per panicle was not significantly impacted by varying water or nutrient management strategies in this experiment. The number of spikelets per panicle was higher in treatment I1T3 (10.0±1.4) over the rest of the treatments in this experiment. It was followed by I2T3 (9.8±1.5), I2T2 treatments (9.8±1.1), then I2T2 treatment (9.6±0.9), and I2T1 treatment (9.4±1.3). The minimum number of spikelets/ panicle (9.2±1.3) was recorded in the I1T1 treatment.

Number of hollow spikelets/ panicle

The results of a statistical analysis of the data (Table 4.13) showed that, independent of the treatments used throughout the experiment, differing water and nutrient management had a significant impact on the number of hollow spikelets per panicle. The number of hollow spikelets per panicle was significantly impacted by varying levels of nitrogen nutrient management during the experiment. Also, the combined effect of water and nutrient management did significantly affect the number of hollow spikelets per panicle in aerobic rice. In the I2T3 treatment, no hollow spikelets per panicle were observed and I2T2 had the maximum hollow spikelet per panicle (5.8±1.6).

Number of grains/ panicle

Statistical analysis observed that the number of grains/ panicle were significantly affected under various nutrition management strategies whereas it failed to exert a significant impact by water management during the experiment, as shown in Table 4.13. I2T3 treatment recorded the highest number of grains per panicle (135.6±12.4). It was followed by I2T2 treatment (101.2±6.9), and I1T2 treatment (92.6±16.8). While, I2T1 treatment was used to record the lowest number of grains per panicle (70.6±18.0), which was followed by I1T1 treatment (82.8±18.1) and I1T3 treatment (89.6±31.1).

Number of filled grains/ panicle

Different management strategies have a significant impact on the quantity of filled grains per panicle. According to the statistical analysis of the data (Table 4.13), the findings demonstrated that varying levels of N nutrient application had a significant impact on the quantity of filled grains per panicle of aerobic rice and resulted in the highest number of filled grains per panicle (94.2±4.2) with I2T3 treatment. It was followed by I2T3 (86.8±18.8), I1T2 treatments (84.0±13.9), then I1T1 treatment (66.2±15.9), and I1T2

treatment (66.2±23.9), respectively. In contrast, the treatment I2T1exhibited the lowest count of filled grains per panicle, with a reported value of 63.4±18.5.

Weight of thousand grains

Statistical analysis of various nutrition and water management strategies on the weight of thousand grains during the experiment is shown in Table 4.13. In this experiment, the thousand grain weight was not affected by either water or nutrient management. Regardless of the various water management strategies and nutrient management strategies used, the weight of 1000 grains in the experiment ranged from 19.3 g to 23.4 g. As in other parameters, I2T3 recorded the highest thousand grain weight (23.4±3.8 g), and it was followed by I2T2 (22.7±6.5 g), I1T3 treatments (21.9±2.7 g), then I2T1 treatment (21.7±4.0 g), and I1T2 treatment (20.5±6.8 g), respectively. While I1T1 treatment recorded the minimum thousand grain weight (19.3±2.9 g).

Harvest index

The harvest index was calculated using each plot's grain and biological (grain + straw) yields. Table 4.13 presents the harvest index and its statistical analysis. Harvest index values varied between the treatments, ranging from 26.9±5.6 to 35.1±6.7 %. Among the treatments, nutrient management significantly influenced the harvest index of rice in this experiment. Regarding water management, the findings showed that during the trial, varying water management did not significantly affect the harvest index of aerobic rice. The experiment's I1T3 (35.4±5.0 %) and I2T3 (35.1±6.7 %) treatments yielded the greatest harvest index. It was followed by I2T2 (33.0±2.3 %), I2T2 treatments (30.4±3.7 %), and then I2T1 treatment (28.3±4.0 %). While I1T1 treatment was recorded as the lowest harvest index (26.9±5.6 %).

Yield

Grain yield recorded from different treatments at harvesting stage was statistically analysed and the results are shown in Table 4.13. Results showed that the yield was significantly influenced by the N management treatment, whereas in the case of water management, even though the yield obtained were different, it was not statistically significant. I2T3 treatment produced the highest grain yield of 4311.8±48.9 kg ha^{-1}, and it was followed by I1T3 (4204.2±213.4 kg ha^{-1}), I1T2 treatments (4004.3±81.4 kg ha^{-1}), then I2T2 treatment (3981.0±85.5 kg ha^{-1}) and I2N1 treatment (3643.6±193.1 kg ha^{-1}), respectively. The treatment I1T1 produced the lowest yield of 3617.3±150.3 kg ha^{-1}.

Table 4.13. Yield characteristics is represented as Mean ± Standard Deviation (SD) of five replications.

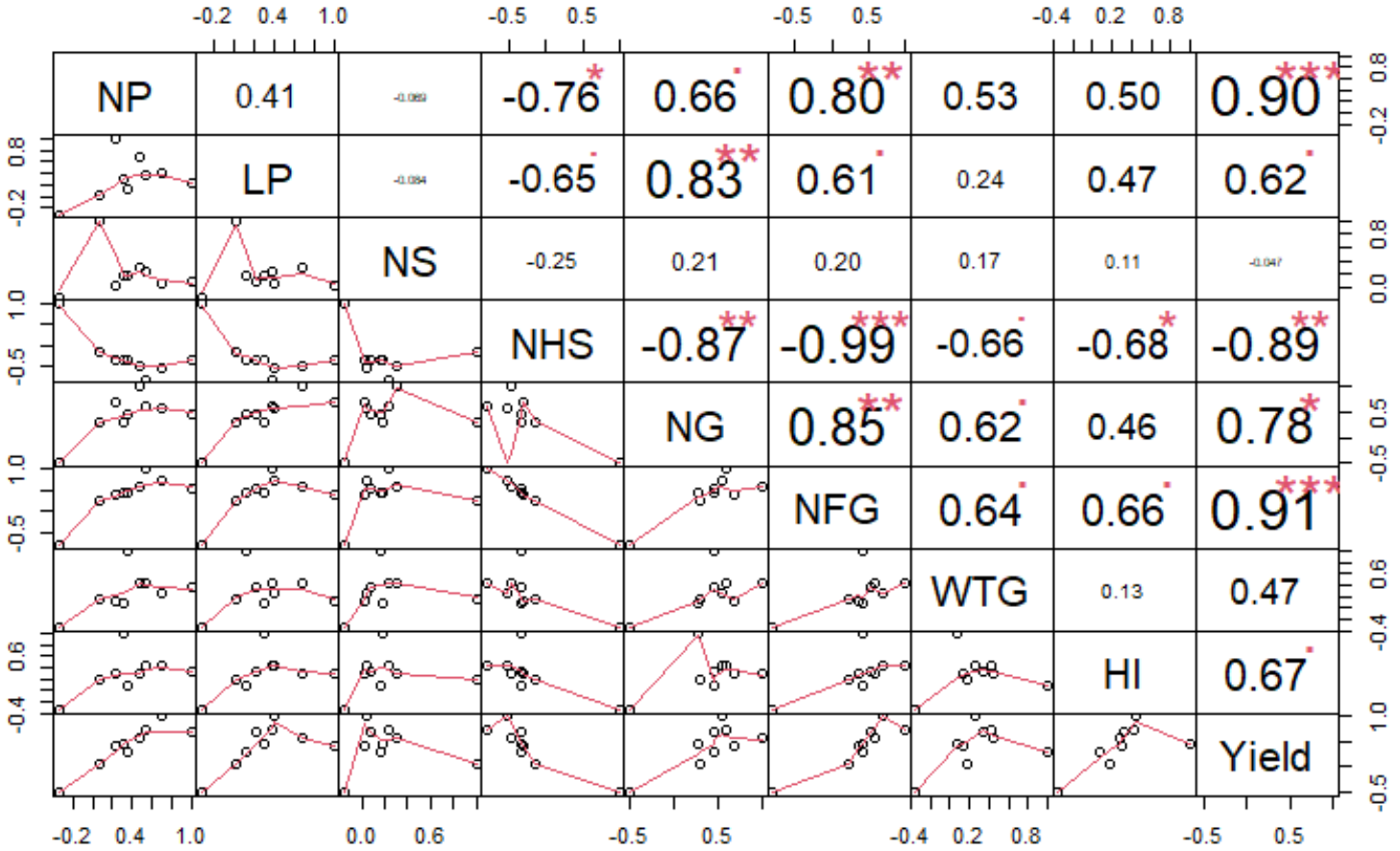
Treatment		No. of Panicles/ tiller	Length of Panicles/ tiller	No. of spikelets/ panicle	No. of Hollow spikelets / panicle	No. of grains in one panicle	No. of Filled grains	Weight of 1000 grains (g)	Harvest Index (%)	Yield (kg ha^{-1})
I1T1		6.2±1.3	18.7±1.7^{ab}	9.2±1.3	3.0±1.0^{bc}	82.8±18.1	66.2±15.9	19.3±2.9	26.9±5.6	3617.3±150.3
I1T2		11.0±2.2	18.6±3.2^{ab}	9.6±0.9	5.2±3.6^{ab}	92.6±16.8	66.2±23.9	20.5±6.8	33.0±2.3	4004.3±81.4
I1T3		12.8±3.9	17.9±2.4^{b}	10.0±1.4	0.2±0.5^{d}	89.6±31.1	86.8±18.8	21.9±2.7	35.4±5.0	4204.2±213.4
I2T1		7.4±3.05	14.7±0.9^{c}	9.4±1.3	5.8±1.6^{a}	70.6±18.0	63.4±18.5	21.7±4.0	28.3±4.0	3643.6±193.1
I2T2		12.2±4.2	17.7±1.6^{b}	9.8±1.1	0.8±1.1^{cd}	101.2±6.9	84.0±13.9	22.7±6.5	30.4±3.7	3981.0±85.5
I2T3		15.2±3.9	20.5±0.9^{a}	9.8±1.5	0.0±0.0^{d}	135.6±12.4	94.2±4.2	23.4±3.8	35.1±6.7	4311.8±48.9
	SE(m)	0.85	0.51	0.35	0.45	5.07	4.56	1.28	1.33	36.66
I	**CV**	30.49	10.91	13.86	70.35	20.59	23	22.95	16.32	3.59
	CD	-	-	-	-	-	-	-	-	-
	SE(m)	1.04	0.62	0.42	0.56	6.21	5.58	1.57	1.63	44.89
T	**CV**	30.49	10.91	13.86	70.35	20.59	23	22.95	16.32	3.59
	CD	3.07	1.84		1.64	18.33	16.48		4.8	132.44
	SE(m)	1.47	0.88	0.59	0.78	8.79	7.9	2.22	2.3	44.89
I X T	**CV**	30.49	10.91	13.86	70.35	20.59	23	22.95	16.32	3.59
	CD	-	2.59		2.32	-				132.44
	I	NS	NS	NS	NS	NS	NS	NS	NS	NS
Fvalue	**T**	**	*	NS	**	**	*	NS	*	**
	I X T	NS	**	NS	**	NS	NS	NS	Ns	NS

Were, I1- 100 % ET_C , I2 – 120 % ET_C , T1- 75 % N- application of inorganic fertilizers, T2- 100 % N application of inorganic fertilizers, T3- 125 % N application of inorganic fertilizer. a, b, c, d, e, and f mean in columns with same superscript do not differ significantly (P< 0.05) *, (P< 0.01) **, LSD test.

4.3.5. Relationship study between yield and other yield characters.

Pearsons's correlation was carried out to study the relationship between yield and other yield parameters, specifically like number of panicles per tiller (NP), length of panicle per tiller (LP), spikelets per panicle number (NS), hollow spikelets per panicle number (NHS), number of grains in one panicle (NG), number of filled grains (NFG), weight of thousand grains (WTG), harvest index (HI). The obtained data are presented in Table 4.14 Paddy yield was positively and significantly correlated with most of the yield parameters as expected and it is negatively correlated with the number of hollow spikelets per panicle(r = - 0.89**). The number of grains in one panicle (r = 0.85**) and the number of panicles per tiller (r = 0.80**) were significantly and synergistically correlated with the number of filled grains. The number of grains and length of the panicle were also significantly and synergistically correlated (r = 0.83**). The number of panicles per tiller (r = - 0.76*), number of grains per panicle (r = - 0.87*), number of filled grains per panicle (r = - 0.99***), harvest index (r = - 0.68*) and yield (r = - 0.89**) were negatively significantly and synergistically correlated with number of hollow spikelets per panicle. Yield characteristics such as the number of panicles per tiller (r = 0.90***), number of grains in one panicle (r = 0.78*), and number of filled grains (r = 0.91***) had strong and positive correlations with grain yield at harvest. Whereas, spikelets number per panicle and weight of thousand grains do not affect on the yield in this experiment.

Table 4.14. Pearson's correlation matrix between yield and yield characters.



The name of each variable is shown on the diagonal, where NP - number of panicles per tiller, LP- length of panicle per tiller, NS -number of spikelets per panicle, NHS- number of hollow spikelets per panicle, NG- number of grains in one panicle, NFG- number of filled grains, WTG- weight of thousand grains, and HI- harvest index HI. On the bottom of the diagonal: the bivariate scatter plots with a fitted line are displayed. On the top of the diagonal: the value of the correlation plus the significance level as stars. Significance level associated to a symbol: p-values (0, 0.001, 0.01, 0.05) -symbols ('***', '**', '*')

Leaf rolling experiment

During the field experiment, the leaf rolling phenomenon was observed in some patches of the experimental plot irrespective of the treatments carried out. Hence, a study was conducted to understand the leaf rolling behaviour and how that can be managed with the help of different moisture-absorbing mediums in upland rice cultivation was evaluated in this experiment and the results are presented hereunder.

4.3.6. Crop biometrics

Crop biometrics consisting of plant height, leaf and tiller number, and panicle length of leaf-rolled plants and healthy plants are summarized in Table 4.15. The plots in which leaf rolling is predominant have been considered as leaf rolling areas under stress based on the visually significant differences and others were considered as healthy plants. Based on that the data have been grouped and used for analysis. Data analysis of the results showed that in aerobic upland rice, leaf-rolled plants and healthy plants showed statistically significant differences among them. Tiller numbers for healthy plants were 7.4±1.1, and 10.8±1.1 whereas the same for leaf-rolling affected plants were 5.8±1.7, and 5.4±1.3 during tillering and maturity, respectively. Healthy plants were found to produce the maximum values for plant height (48.8±10.3 cm, 55.4±6.5 cm, and 81.2±2.6 cm for tillering, flowering and maturity stages respectively), root length (14.7±1.1cm, 15.9±1.7 cm, and 17.7±0.5 cm for tillering, flowering and maturity stages respectively) and length of panicle (19.9±1.9 cm, and 23.5±2.1 cm for flowering and maturity stages respectively) over plants with leaf rolling phenomena in every observed phase. The lowest values for plant height (30.6±3.5 cm, 33.6±4.7cm, and 52.1±9.5 cm for tillering, flowering and maturity stages respectively), root length (3.8±2.1 cm, 9.4±2.0 cm, and 12.8±1.5 cm for tillering, flowering and maturity stages respectively) and length of panicle (13.7±2.3 cm, and 14.6±2.5 cm for flowering and maturity stages respectively) were observed for the leaf rolling plants. In the case of shoot biomass and root biomass, the same patterns were observed. The shoot biomass of healthy plants (16.5±2.3 g, 35.3±1.3 g, and 45.2±1.5 g for tillering, flowering and maturity stages respectively) was significantly higher than the shoot biomass of leaf rolling plants (8.2±0.8 g, 8.3±0.4 g, and 9.4±2.2 g for tillering, flowering and maturity stages respectively). Also, the root biomass of healthy plants (8.9±2.2 g, 4.8±0.9 g, and 6.9±1.8 g for tillering, flowering and maturity stages respectively) were significantly higher than the root biomass of leaf rolling plants (1.9±0.6 g, 1.2±0.5 g, and 2.5±1.7 g for tillering, flowering and maturity stages

respectively). The number of panicles per hill was 12.8±1.8 and 15.3±2.3 for the flowering and maturity stages of healthy plants, which were higher in comparison to leaf rolling affected plants (6.4±1.1 and 7.2±0.8 for flowering and maturity, respectively).

Table 4.15. Crop biometric data on leaf rolling affected and healthy plants

Parameters		Tillering	Flowering	Maturity
No. of tillers	**Healthy**	7.4±1.1	10.8±1.1	10.8±1.1
	Rolling	5.8±1.7	5.4±1.8	5.4±1.3
	t stat value	1.99	6.04	4.49
	t stat	**	**	**
Plant height (cm)	**Healthy**	48.8±10.3	55.4±6.5	81.2±2.6
	Rolling	30.6±3.5	33.6±4.7	52.1±9.5
	t stat value	3.75	7.35	4.97
	t stat	**	**	**
Root length (cm)	**Healthy**	14.7±1.1	15.9±1.7	17.7±0.5
	Rolling	3.8±2.1	9.4±2.0	12.8±1.5
	t stat value	7.93	6.45	5.44
	t stat	**	**	**
Shoot biomass (g)	**Healthy**	16.5±2.3	35.3±1.3	45.2±1.5
	Rolling	8.2±0.8	8.3±0.4	9.4±2.2
	t stat value	6.24	35.09	22.38
	t stat	**	**	**
Root biomass (g)	**Healthy**	8.9±2.2	4.8±0.9	6.9±1.8
	Rolling	1.9±0.6	1.2±0.5	2.5±1.7
	t stat value	6.16	7.48	10.3
	t stat	**	**	**
No. of panicles	**Healthy**		12.8±1.8	15.3±2.3
	Rolling		6.4±1.1	7.2±0.8
	t stat value		4.36	5.94
	t stat		**	**
Length of panicle (cm)	**Healthy**		19.9±1.9	23.5±2.1
	Rolling		13.7±2.3	14.6±2.5
	t stat value		4.81	4.82
	t stat		**	**

4.3.7. Soil moisture

The soil's microclimatic region is mainly determined by its moisture content. Soil moisture content varies slowly with respect to changes in its land–atmosphere system and it depends on the irrigation practices. In this study, an average of 33.94 ± 4.97 % volumetric water content (VWC) was observed for soil areas with healthy plants with a moisture range of 29.7 to 44.6 % VWC. Whereas 22.48 ± 3.59 % volumetric water content was observed for soil patches with leaf-rolled paddy plants with a moisture range of 16.5 to 27.7 % VWC (Fig. 4.5).

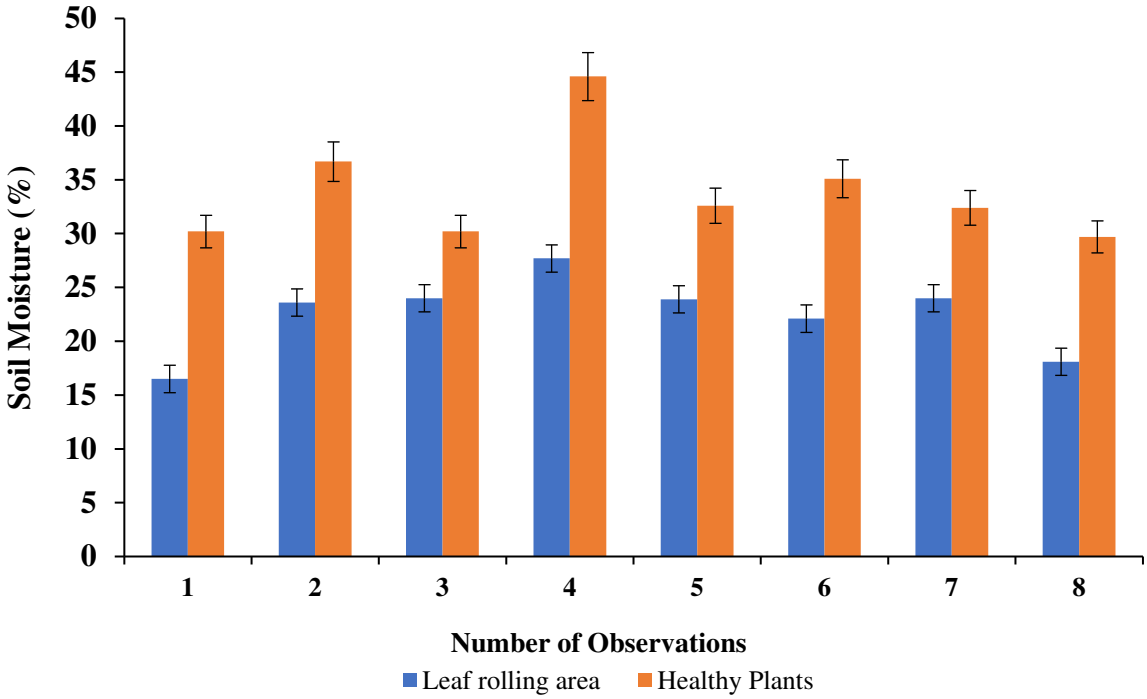


Fig. 4.5. Soil moisture in leaf rolling affected area and healthy plants area

4.3.8. Relative water content and Membrane leakage

Relative water content (RWC) and membrane leakage (ML) are treated as the major indicators for understanding the water status/ stress in plants. To assess the intensity of the stress, the plants were observed initially using visual indicators to confirm the visual rating, and chosen plants were subjected to RWC and ML analysis. The results of the RWC analysis showed that leaf samples from the stressed plants (leaf rolling) exhibited an RWC ranging from 30–50 %, whereas for the healthy plants, RWC is 72-85 % (Fig.4.6). The results ML analysis showed that leaf samples from the stressed plants were exhibited an ML ranging from 21–32 %, whereas for the healthy plants ML is 15-18 % (Fig.4.7).

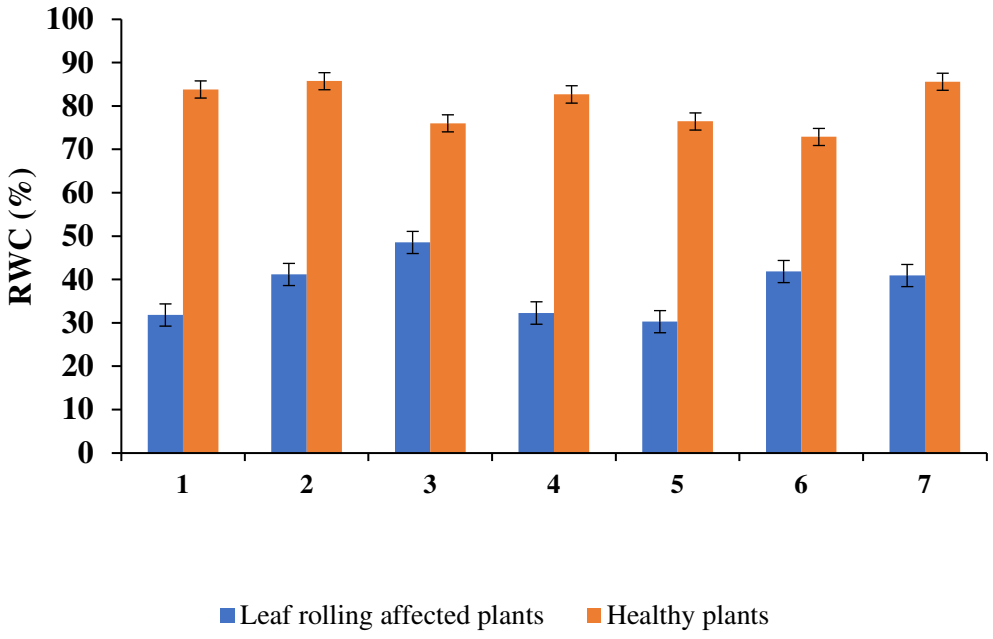


Fig. 4.6. Relative water of leaf rolling affected plants Vs Healthy plants

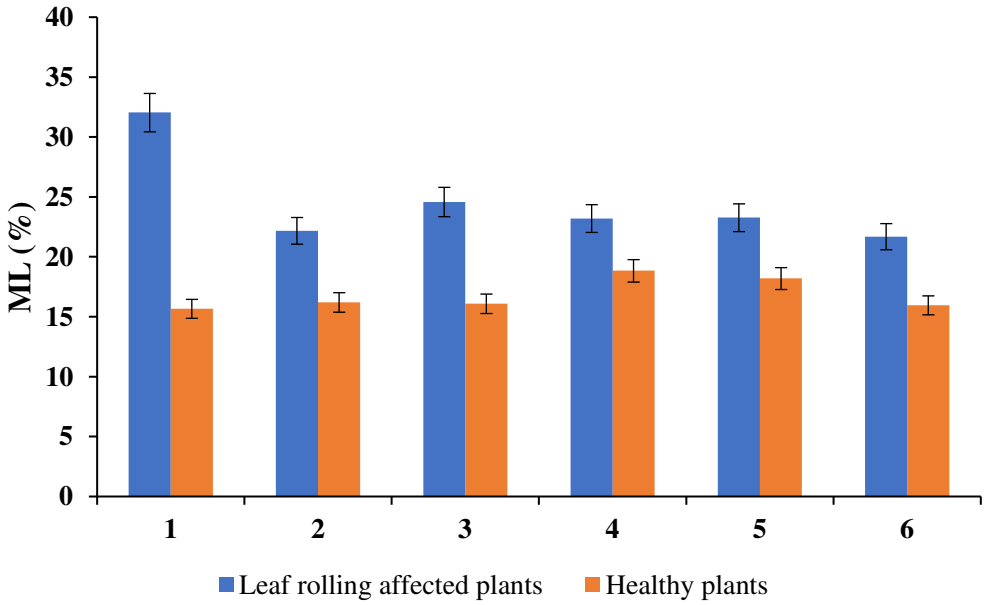


Fig. 4.7. Membrane Leakage of leaf rolling affected plants Vs Healthy plants

Similarly, in subsequent experiments with the addition of moisture-absorbent materials in soil, RWC was significantly influenced by these treatments. Healthy plants recorded higher RWC (86.45 %) and it was on par with cocopeat added treatments (85.12%) and they were statistically significant when compared with other moisture-absorbent materials (Table 4.16). Other materials such as compost (78.46 %), sawdust (79.41 %) and vermiculite (79.56 %) performed on-par in recovering the RWC with the

help of these moisture absorbents and the least RWC was recorded in soil alone and leaf rolling affected area (52.46 %).

Similar results were observed in membrane leakage (ML) too. Membrane leakage of the leaf samples from the stressed plants was significantly higher than the healthy plants (16.84 %). In the case of moisture absorbent media study also, ML was significantly influenced by the treatments i.e. addition of moisture absorbent materials. Healthy plants recorded low ML (16.84 %) and it was on par with cocopeat added treatments (17.48 %) and they were statistically significant when compared with other moisture-absorbent materials (Table 4.16). Other materials such as compost (21.42 %), saw dust (20.54 %) and vermiculite (19.85 %) performed equally in maintaining the ML and the high ML was recorded in soil alone and leaf rolling affected area (31.20 %).

Table 4.16. Relative water content (RWC) and membrane leakage (ML) of leaf rolled plants treated with different soil moisture absorbent materials. Data showed as average ± standard deviation of five samples. Level of significance considered as P value * <0.01 and different alphabet letters indicated the significant difference

Soil + Moisture absorbent materials	RWC (%)	ML (%)
Healthy plants	86.45[a]	16.84[a]
Cocopeat	85.12[a]	17.48[a]
Compost	78.46[b]	21.42[b]
Sawdust	79.41[b]	20.54[b]
Vermiculite	79.56[b]	19.85[b]
Control leaf rolling	52.46[c]	31.20[c]

4.3.9. Spectral reflectance

Spectral reflectance data showed a significant difference between water-stressed plants (leaf rolling affected) and healthy plants (Fig.4.8). In the healthy plants the reflectance was lower because the growth of rice is good and hence water content is ideal, which is evident from the lab analysed values of RWC and other biometric parameters. This validates the potential use of the observed indices from the spectroradiometer for identifying such plant stress conditions The differences across the spectral signature curves are well evident between stressed and healthy plants in two stages (Flowering and maturity) compared to the initial stage of tillering.

The spectral signatures clearly revealed the presence of four significant absorption troughs in the Near-infrared (NIR 750–1,300 nm) and Short-wavelength infrared (SWIR 1,300–2,500 nm) regions. These spectral reflectance troughs, positioned approximately at 970 and 1,175 nm in the NIR, and at 1,450 and 1,950 nm in the SWIR, are attributed to water absorption and are consistently observed in both healthy and stressed plants. Troughs around 1,450 and 1,950 nm exhibit a less pronounced character, particularly in plants experiencing a high degree of water deficit due to stress.

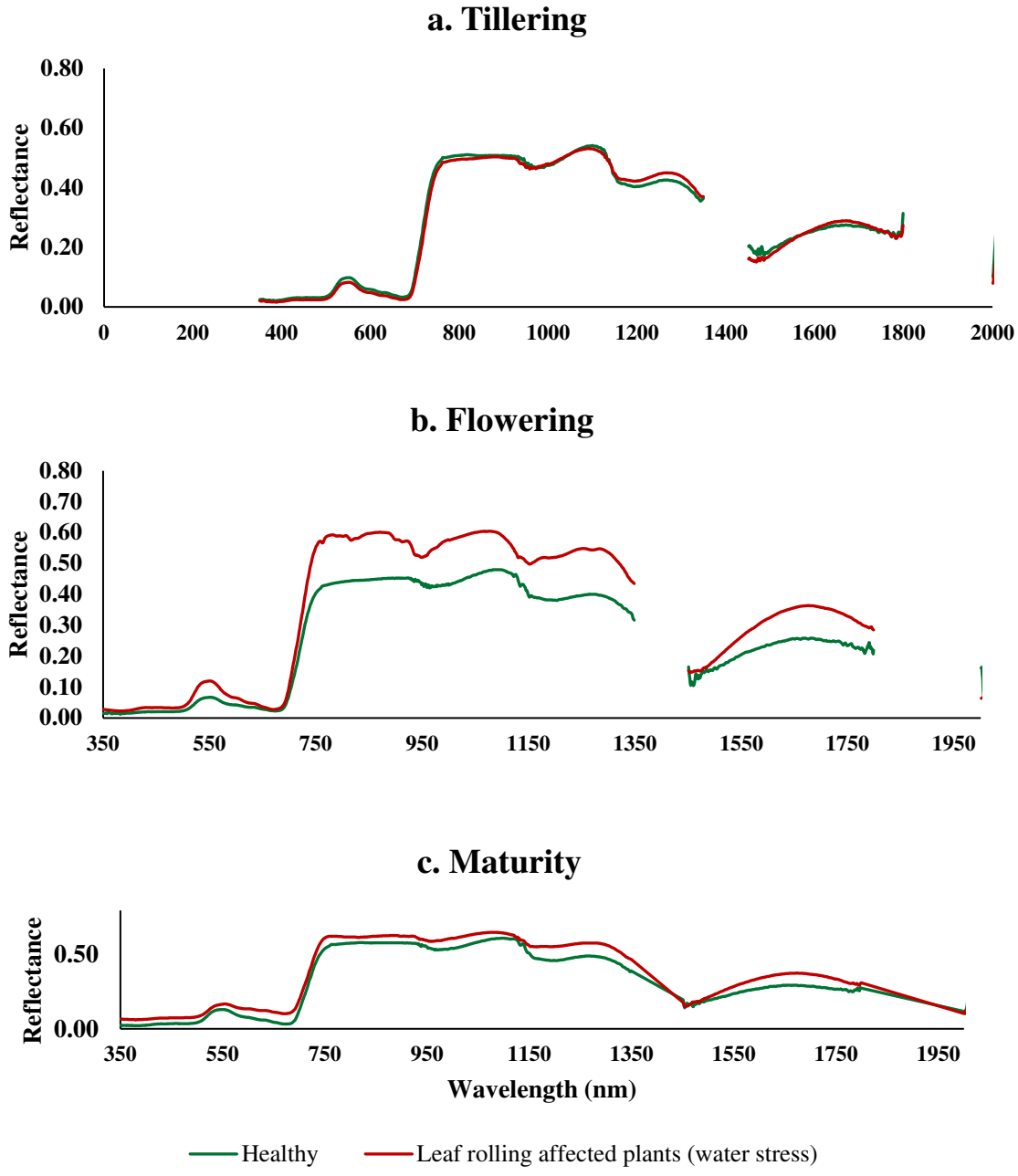
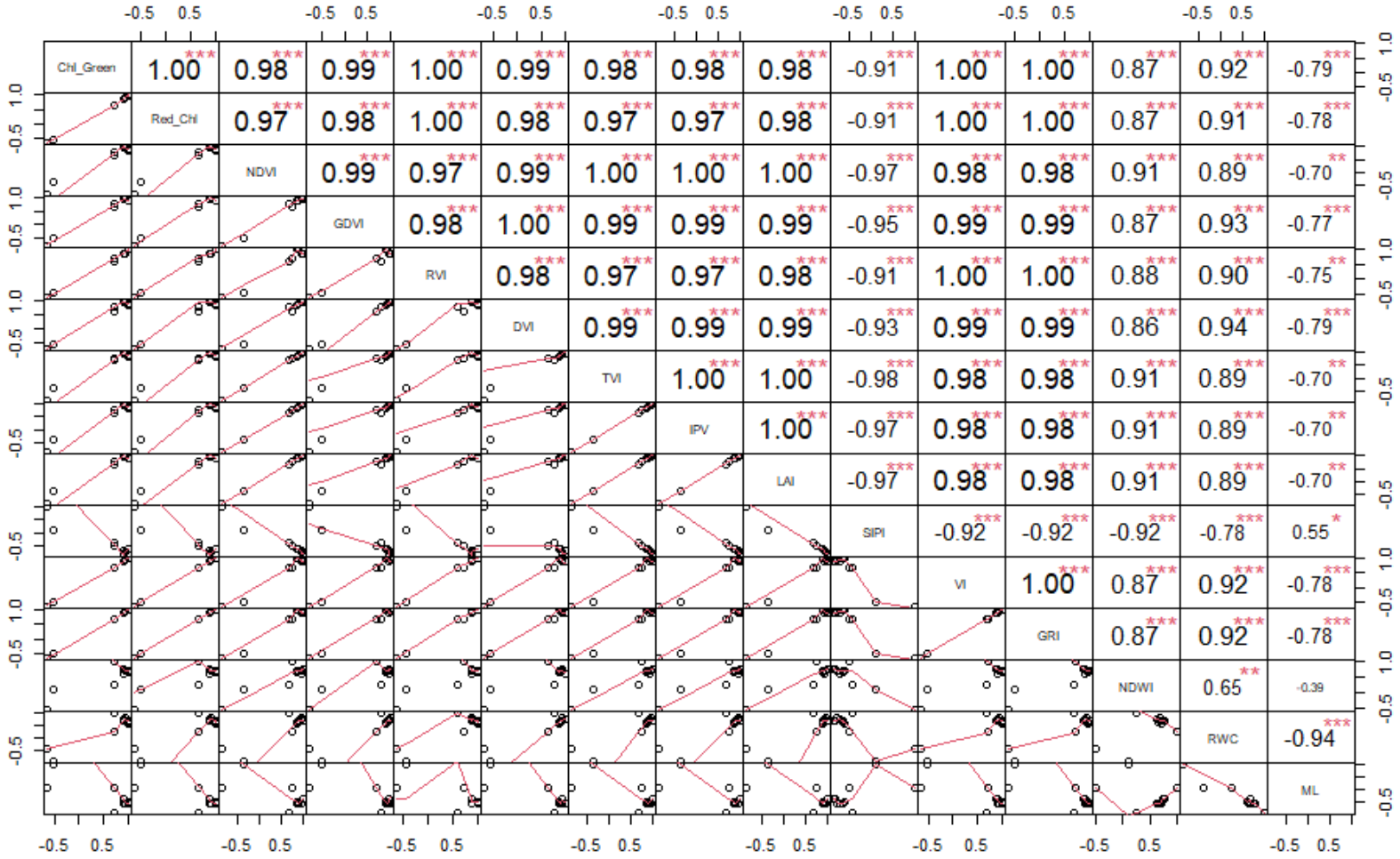


Fig.4.8. Paddy spectral reflectance of healthy and leaf rolling affected plants at three different stages

4.3.10. Correlation study between spectral indices with RWC and ML

Several vegetative indices were computed from the spectral data and these calculated spectral indices were correlated with RWC and ML to understand whether such indices have any direct relationship with water stress. The results were further confirmed with Pearson correlation analysis and results showed a strong positive correlation ($P < 0.05$) of key spectral indices with other physiological traits such as RWC and negatively correlated with membrane leakage. The other indices such as chlorophyll content, LAI, NDVI and NDWI and most of the spectral indices were correlated well between themselves (Table 4.17). Green chlorophyll (CL(G)) was significantly and perfectly correlated with red Chl ($r = 1$), RVI ($r = 1$), VI ($r = 1.00$) and GRI ($r = 1.00$) and was high-positively correlated to NDVI ($r = 0.98$), GDVI ($r = 0.99$), DVI ($r = 0.99$), TVI ($r = 0.98$), IPV ($r = 0.98$), LAI ($r = 0.98$), NDWI ($r = 0.87$), and RWC ($r = 0.92$). Red chlorophyll (red chl) was significantly and perfectly correlated with RVI ($r = 1$), VI ($r = 1.00$) and GRI ($r = 1.00$). Red chlorophyll (red chl) was significantly and high-positively correlated to NDVI ($r = 0.97$), GDVI ($r = 0.98$), DVI ($r = 0.98$), TVI ($r = 0.97$), IPV ($r = 0.97$), LAI ($r = 0.98$), RWC ($r = 0.91$), and NDWI ($r = 0.87$). NDVI was significantly and perfectly correlated with TVI ($r = 1$), IPV ($r = 1.00$) and LAI ($r = 1.00$). NDVI was significantly and high-positively correlated to GDVI ($r = 0.99$), RVI ($r = 0.97$), DVI ($r= 0.99$), VI ($r = 0.98$), GRI ($r = 0.98$), NDWI ($r = 0.91$), and RWC ($r = 0.89$). GDVI perfectly correlated with DVI ($r = 1$) and was significantly and high-positively correlated to RVI ($r = 0.98$), TVI ($r = 0.99$), IPV ($r = 0.99$), LAI ($r = 0.99$), VI ($r = 0.99$), GRI ($r = 0.99$), RWC ($r = 0.93$), and NDWI ($r = 0.87$). RVI perfectly correlated with VI and GRI ($r = 1$) and was significantly and high-positively correlated DVI ($r = 0.98$), TVI ($r = 0.97$), IPV ($r = 0.97$), LAI ($r = 0.98$), NDWI ($r= 0.88$), and RWC ($r = 0.90$). DVI was significantly and high-positively correlated TVI ($r = 0.99$), IPV ($r = 0.99$), LAI ($r = 0.99$), VI ($r = 0.99$), GRI ($r = 0.99$), RWC ($r = 0.94$), and NDWI ($r = 0.86$). Also, TVI & IPV, LPVI & LAI and TVI & LAI were perfectly correlated with each other. TVI was significantly and high-positively correlated VI ($r = 0.98$), GRI ($r = 0.98$), NDWI ($r = 0.91$) and RWC ($r = 0.89$). IPV was significantly and high-positively correlated with VI ($r = 0.98$), GRI ($r = 0.98$), NDWI ($r = 0.91$) and RWC ($r = 0.89$). LAI was significantly and high-positively correlated VI ($r = 0.98$), GRI ($r = 0.98$), NDWI ($r = 0.91$) and RWC ($r = 0.89$). VI and GRI are perfectly correlated ($r = 1$) and was significantly corelated with RWC ($r = 0.92$) and NDWI ($r = 0.87$). GRI was also significantly correlated with RWC ($r = 0.92$) and NDWI ($r = 0.87$). RWC was positively and significantly correlated with all spectral indices except SIP and ML. SIPI and ML were negatively correlated with RWC and the rest of the spectral indices.

Table 4.17. Pearson's correlation matrix between different indices based on spectral signatures and lab analyzed values of RWC and ML



Where, NDVI- Normalized Difference Vegetation Index; GDVI- Generalized Difference Vegetation Index; LAI- Leaf Area Index; VI- Vegetation Index, RVI- Ratio Vegetation Index/ Simple Ratio; GRI- Green Ratio Index; DVI- Direct Vegetation Index; TVI- Transformed Vegetation Index; Cl(G)- Green Chlorophyll Index; Cl(R)- Red-edge Chlorophyll Index; SIPI- Structure Insensitive Pigment Index; IPVI- Infrared Percentage Vegetation Index; NDWI- Normalized Difference Water Index; RWC- Relative water content; ML- Membrane leakage.

Pot culture experiment

4.3.11. Observations

The pot culture experiment results showed significant differences in water stress on the visual scoring method (data not shown). It was recorded that, on different days of drought stress leaves started rolling and drying. After four days, the curling of paddy leaves was first observed in the pot with soil alone as a potting mixture. The paddy plants grown in a potting mixture of both soil and cocopeat started rolling after 7 days. This was repeated a few times to make sure about the reproducibility with the help of replicates. After standardization of the same, recovery of plants from rolling was attempted by adding water and the results were observed. After both plants completely rolled, water was added until they recovered to their normal state and the time taken for the same was noted. It was noted that the plants that are grown in the pot (T2) containing the mixture of both soil and cocopeat, regain their normal state rapidly (30 minutes) after the addition of water. Compared with T2, the plants potted in soil alone took more time (36 hours) to recover fully from the leaf rolling (Video). These results suggest that for aerobic rice the soil incorporated with moisture-absorbent media such as cocopeat can reduce the rate of leaf rolling thereby sustaining the paddy yield.

4.4. Experiment -4

The results acquired from the research work entitled "*Assessing the influence of different organic management practices on farmer's paddy yield"* were collected and elucidated hereunder. This experiment was done in the farmer's field with the *Karuna* rice cultivar and it was done to assess the effect of different organic management practices.

4.4.1. Experimental soil and site characteristics

The soil in the experimental plot is classified as lateritic and falls within the Kunnamangalam series, belonging to the USDA class of Mixed; Isohyperthermic, Typic Kanhaplustults. The initial physico-chemical characteristics of the soil are outlined in Table 4.18. The soil pH is recorded at 6.41, with an electrical conductivity (EC) of 55.04 mS m^{-1}. The field capacity and wilting point of the experimental soils are measured at 26.41 % and 13.53 %, respectively. Initial soil composition includes organic carbon content of 0.85 %, available nitrogen (N) at 192.00 kg ha^{-1}, available phosphorus (P) at 19.01 kg ha^{-1}, and available potassium (K) at 123.68 kg ha^{-1}. Besides, the soil contains

1.90 mg kg^{-1} of Zinc, 12.60 mg kg^{-1} of iron, 0.23 mg kg^{-1} of boron, 3.19 mg kg^{-1} of calcium, and 1.30 mg kg^{-1} of magnesium

Table 4.18. Initial soil physical and chemical parameters of experimental plot

Parameters	
pH	6.41
Electrical conductivity (mS m^{-1})	55.04
Field capacity (%)	26.41
Wilting point (%)	13.53
Organic carbon (%)	0.85
Available N (kg ha^{-1})	192.00
Available P (kg ha^{-1})	19.01
Available K (kg ha^{-1})	123.68
Zinc (mg kg^{-1})	1.90
Iron (mg kg^{-1})	12.60
Boron (mg kg^{-1})	0.23
Calcium (mg kg^{-1})	3.19
Magnesium (mg kg^{-1})	1.30

4.4.2. Climatic parameters

The experimental field site experiences a humid tropical climate characterized by hot dry summer season and chill winter seasons. The region falls under the climate of humid tropical. The maximum temperature experienced in the experimental location during the crop period was 34.5 ^{0}C and the minimum temperature that prevailed during the experimental period was 18.0 ^{0}C. Throughout the crop period, total rainfall received was 1674.9.1 mm. Average maximum relative humidity and minimum relative humidity were found 98.0 % and 62.0 % respectively during the experimental period. Weather experienced during the experimental period is graphically represented in Fig.4.9.

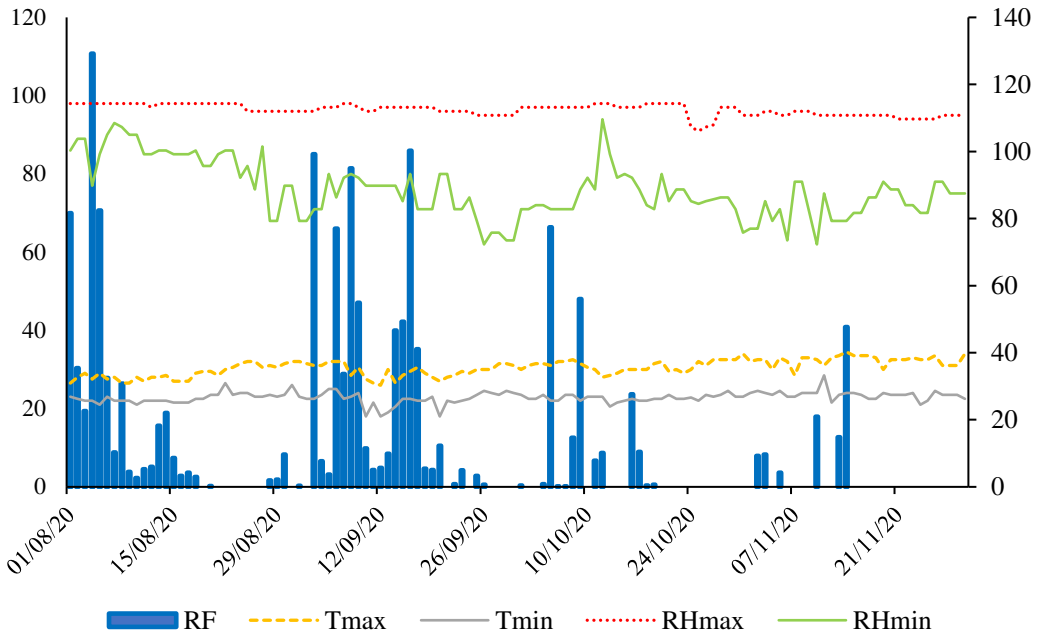


Fig.4.9. Weather data during crop growth period- Experimental 4

4.4.3. Biometric characteristics

Crop biometric parameters showed that the organic fertilizer management practices influenced the parameters significantly and the data are shown in Table 4.19. The results exhibited that the *Karuna* cultivar treated with both compost and Azolla with basal nutrients (P4) produced higher growth parameters followed by treatment with the application of Azolla with basal nutrients (P3), and application of compost with basal nutrients (P2), The least crop morphological parameters were produced by farmer's traditional management practices (C). Hence the treatment, compost and Azolla with basal nutrients performed better when compared to the other treatments. Growth attributes consisting of the number of tillers, plant height, LAI, root length, and number of panicles were observed and studied in this experiment.

Plant height

The plant height was influenced significantly by different fertilizer management strategies in all observed stages of crop growth viz., tillering, flowering, and harvest stages. Maximum plant height was recorded with compost and Azolla along basal nutrients (P4) treatments which was statistically superior to the rest of the treatments in all the stages of crop growth, and the highest plant height recorded was 69.2±2.6 cm at tillering, 109.8±13.1 cm at flowering and 137.7±22.7 cm at harvest. This was followed by P3

treatment, 65.5±2.9 cm at tillering, 102.9±9.3 cm at flowering and 118.2±15.4 cm at harvest, and P2 treatment, which recorded the plant height of 60.6±3.9 cm at tillering, 97.7±57 cm at flowering and 108.2±9.8 cm at harvest. The lowest plant height was recorded in plants treated with the application of basal nutrients (P1) only (53.7± 3.8cm) at tillering, whereas in flowering and harvest, P1 showed the least plant height, 83.6 ± 12.6 cm, 100.5 ± 11.6 cm respectively and it was followed by treatment C, in which at flowering, 95.2±7.9 cm, treatment C in harvest, 105.2±11.5 cm was observed.

Number of tillers

Variations in organic amendments significantly influenced the number of tillers in this experiment. The highest number of tillers/ hill was recorded in the P4 treatment (16.2±1.3) which was followed by the P_3 treatment and the P2 treatment (13.0± 1.4 and 12.8 ± 1.8, respectively) which were statistically on par. Whereas, the lowest values were observed for P1 and C treatments (11.4±0.9 and 11.0± 1.0, respectively) which were also statistically on par at the tillering stage. During the flowering stage, the highest number of tillers was observed with the P4 treatment (16.0±2.0), which was the superior treatment and the lowest for P1 (9.6±1.1), which was the inferior treatment. At harvest, the highest number of tillers per hill was recorded in P4 treatment (16.0±1.5) followed by P3 treatment (12.2±1.1), and P2 and C (10.6±1.9 and 10.6±0.7, respectively) which were on-par and the lowest was observed for P1 treatment (9.2±1.9).

LAI

The leaf area index (LAI) computed during the experiments was tabulated in Table 4.19. In the *Karuna* rice variety, different organic treatments had a significant impact on the LAI during all three stages. Among the treatments, treatment C (1.1±1.3) had the least LAI during the tillering stage and the highest for treatment P4 (2.1±0.7). During the flowering, the highest average values for LAI for the P4 treatment 4.7±0.8, which was followed by the P3 treatment 3.8±0.9, and the P2 treatment, 3.2±1.1. The least was observed for treatment C, 2.7±1.1. In this stage P4 treatment was superior and C treatment was inferior among the treatments. During the harvesting stage, P4 treatment has the highest values for LAI, i.e., 2.1±1.2, followed by P3 treatment, 1.6±0.5, and C treatment, 1.3±1.1. The lowest value was observed for P1 and P2 treatments (1.1±1.2 and 1.1±0.4) which were statistically on par and inferior among treatments.

Root length

Organic amendments significantly influence the length of roots in this experiment. The longest root was recorded in P4 treatment (9.8±1.3 cm) followed by P3 treatment (8.5±0.8 cm) which were statistically on-par. Lowest value was recorded for P1 (5.2±0.8cm) which was also statistically on-par with P2 (6.3±0.6 am), and C(6.1±1.1 cm) treatments at tillering stage C treatment and lowest for. During flowering highest value for root length was observed for P4 treatment (14.6±1.8 cm) and lowest for P1 treatment (8.2±1.8 cm), respectively. At harvest stage, highest value for root length was recorded in P4 treatment (20.6±0.9 cm) followed by P3 treatment (17.8±1.0 cm), then P2 treatment (15.9±1.5cm) and C (14.3±2.0 cm) and lowest was observed for P1 treatment (13.6±2.0 cm). P4 treatment was found to be superior and P1 treatment was found to be inferior statistically.

Number of panicles

The number of panicles observed during the flowering and harvesting stage were tabulated in Table 4.19. Different organic fertilizer management had a statistically significant effect on panicle production. Among the treatments, the highest values for the number of panicles were observed in the P4 treatment, i.e., 14.0±2.7 and 18.8±1.8, for the flowering and the harvesting stages, respectively. It was followed by P3 treatment, , i.e., 11.6±1.4 and 16.2±0.8, for the flowering and the harvesting stages respectively. The P2 treatment, recorded 9.6±1.5 and 14.2±0.8 for the number of panicles at flowering and harvesting stages, respectively, and this was followed by the C treatment, which recorded the values of i.e., 8.6±1.5 and 10.4±3.6, for the flowering and the harvesting stages respectively. The lowest number of panicles were noticed in P1 treatment, i.e., 8.4± 0.9 and 9.8± 0.9 in both flowering and harvesting stages respectively.

4.4.4. Post-harvest soil chemical parameters

Analysis of chemical soil parameters after post-harvest revealed a significant influence of organic nutrient application practices on these parameters, as detailed in Table 4.20. The concentration of major soil macronutrients exhibited a significant increase with all organic amendments compared to the initial conditions. But had not shown any significant effect on other macro and micronutrients. Soil pH and electrical conductivity failed to have a significant effect by organic management and its values ranges from

6.0±0.6 to 6.±0.5 and 48.3±5.0 mS m^{-1} to 59.4±5.0 mS m^{-1}, respectively. Soil pH of experimental plots belongs to the medium acidic category.

Organic amendments significantly influence the organic carbon (OC) content of the soil. OC of experimental plots belongs to the high-level category except for the P1 treatment plot which belongs to the medium-level category. The highest value for OC was recorded in the plot with P4 treatment (1.2±0.3 %) followed by P3 treatment plot (1.1±0.3 %), P2 treatment plot (1.0±0.3 %), then C plot (0.8±0.1 %) and lowest OC was recorded in P1 treatment plot (0.6±0.1 %). A similar pattern was observed for available N and the highest value for available nitrogen was observed in the plot with P4 treatment (317.5±17.4 kg ha^{-1}), which is followed by the P3 treatment plot (238.9±25.9 kg ha^{-1}) and P2 treatment plot (233.5±45.9 kg ha^{-1}), which were on-par and lowest N was observed in P1 (122.3±10.0 kg ha^{-1}) treatment. Among the samples majority of the sample falls under low nitrogen content except P4 treatment plot sample, which belongs to the medium-level category.

The highest value for available P in soil was recorded for P4, followed by P3 and P2 treatment plots, 32.2±6.0 kg ha^{-1}, 32.3±6.5 kg ha^{-1}, 30.7±4.6 kg ha^{-1} respectively, which were statistically on-par. The lowest was measured for P1 treatment plot i.e., 12.8±4.7 kg ha^{-1}. Among the samples, the majority of the sample falls under high P content except the the P1 treatment plot sample, which belongs to the medium-level category. The highest value for potassium was found for the P4 treatments plot (262.5±15.1 kg ha^{-1}) and the least for the control (C) plot (145.7±27.3 kg ha^{-1}). Here, all the experimental plots belong to the medium category in soil potassium status.

Soil micro nutrients such as Zn, Fe and B pH failed to show any significant effect by organic management and its values ranges from 1.5±0.5 mg kg^{-1} to 2.5±0.5 mg kg^{-1}, 10.2±2.4 mg kg^{-1} to 14.4±1.6 mg kg^{-1}, and from 0.4±0.1 mg kg^{-1} to 0.6±0.1 mg kg^{-1}, respectively. All the experimental plots contained a minimum level of micronutrients for plant growth. Calcium (Ca) content in the experimental site is ranged from 7.5±1.7 mg kg^{-1} for P4 treatment plot to 3.0±2.6 mg kg^{-1} for P2 experimental plot. P4 treatment plot (3.1±0.5 mg kg^{-1}), P3 treatment plot (2.4±0.4 mg kg^{-1}), P2 treatment plot (1.5±1.2 mg kg^{-1}), P1 treatment plot (1.3±1.4 mg kg^{-1}), and C treatment plot (1.2±1.1 mg kg^{-1}) were determined to have the highest to lowest values for magnesium content.

Table 4.19. Growth characteristics such as number of tillers, plant height, LAI, root length and number of panicles of *Karuna* rice verity, is represented as Mean ± Standard Deviation (SD) of four replications.

Treatments	No. of Tillers	Plant Height (cm)	LAI	Root length (cm)	No. of Panicles
TILLERING					
P.1	11.4±0.9^{c}	56.6±4.3^{cd}	1.1±0.8^{d}	5.2±0.8^{b}	
P.2	12.8±1.8^{b}	60.6±3.9^{bc}	1.5±1.4^{c}	6.3±0.6^{b}	
P.3	13.0±1.4^{b}	65.5±2.9^{ab}	1.8±0.7^{b}	8.5±0.8^{a}	
P.4	16.2±1.3^{a}	69.2±2.6^{a}	2.1±0.7^{a}	9.8±1.3^{a}	
C	11.0±1.0^{c}	53.7±3.8^{d}	1.1±1.3^{d}	6.1±1.1^{b}	
F value	*	*	*	*	
SE(m)	0.45	1.67	0.88	0.44	
CD	1.36	5.00	2.63	1.30	
CV (%)	7.90	6.11	12.96	13.52	
FLOWERING					
P.1	9.6±1.1^{c}	83.6±12.6^{d}	2.8±1.3^{cd}	8.2±1.8^{c}	8.4±0.9^{c}
P.2	12.2±1.3^{b}	97.7±5.7^{bc}	3.2±1.1^{c}	10.3±0.8^{b}	9.6±1.5b^{c}
P.3	12.4±1.1^{ab}	102.9±9.3^{b}	3.8±0.9^{b}	11.5±1.1^{b}	11.6±1.5^{ab}
P.4	16.0±2.0^{a}	109.8±13.1^{a}	4.7±0.8^{a}	14.6±1.8^{a}	14.0±2.7^{a}
C	11.0±0.9^{b}	95.2±7.9^{c}	2.7±1.1^{d}	9.7±1.1^{bc}	8.6±1.5^{c}
F value	*	*	*	*	*
SE(m)	0.59	Inf	1.65	0.67	0.84
CD	1.75	9.35	4.93	1.99	2.52
CV (%)	10.97	7.10	10.69	13.70	18.02
HARVEST					
P.1	9.2±1.9^{c}	100.5±11.6^{c}	1.1±1.2^{d}	13.6±2.0^{d}	9.8± 0.9^{d}
P.2	10.6±1.7^{bc}	108.2±9.8^{bc}	1.1±0.4^{c}	15.9±1.5^{bc}	14.2±0.8^{bc}
P.3	12.2±1.1^{b}	118.2±15.4^{b}	1.6±0.5^{b}	17.8±1.0^{b}	16.2±0.8^{b}
P.4	16.0±1.5^{a}	137.7±12.7^{a}	2.1±1.2^{a}	20.6±0.9^{a}	18.8±1.8^{a}
C	10.6±0.9^{bc}	105.2±11.5^{bc}	1.3±1.1^{d}	14.3±2.0^{cd}	10.4±3.6^{c}
F value	*	*	*	*	*

SE(m)	0.71	5.63	1.09	0.60	0.84
CD	2.14	16.87	3.26	1.81	2.52
CV (%)	13.46	11.04	7.99	8.20	12.98

Where, P1- Application of basal nutrients only (FYMs); P2- Application of compost with basal nutrients and P3- Application of Azolla with basal nutrients, P4- Application of both compost and Azolla with basal nutrients, and C- Farmer's traditional management practices. a, b, c, d, e, and f mean in columns with same superscript do not differ significantly (P< 0.05) *, LSD test. SEM: Standard Errors of Mean; CD: Critical difference; CV: Coefficient of variance.

Table 4.20. Post harvest soil analysis plot wise results are represented as Mean ± Standard Deviation (SD) of four replications.

Treatments	pH	EC	OC (%)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Zn (mg kg^{-1})	Fe (mg kg^{-1})	B (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})
P.1	6.0±0.6	50.3±4.1	0.6±0.1	122.3±10.0^{c}	12.8±4.7^{b}	172.4±50.8	1.5±0.5	10.2±2.4	0.4±0.1	4.7±1.7	1.3±1.4
P.2	6.5±0.2	48.3±5.0	1.0±0.3	233.5±45.8^{b}	30.7±4.6^{a}	167.4±34.9	2.3±0.2	13.6±2.9	0.5±0.1	3.0±2.6	1.5±1.2
P.3	6.5±0.5	54.3±8.4	1.1±0.3	238.9±25.9^{b}	32.3±6.5^{a}	216.2±14.4	2.5±0.4	14.4±1.6	0.4±0.1	4.9±2.3	2.4±0.4
P.4	6.2±0.1	59.4±5.0	1.2±0.3	284.3±17.4^{a}	32.2±6.0^{a}	262.5±15.1	2.5±0.5	13.7±1.9	0.6±0.1	7.5±1.7	3.1±0.5
C	6.4±0.5	53.9±7.4	0.8±0.1	185.0±62.5^{bc}	21.4±2.2^{ab}	145.7±27.3	1.85±0.3	13.6±0.6	0.5±0.1	4.8±1.8	1.2±1.1
F value	NS	NS	*	**	**	NS	NS	NS	NS	NS	NS
SE(m)	0.24	3.58	0.15	21.71	2.90	18.22	0.23	1.71	0.06	1.18	0.57
CD	-	-	0.48	68.42	9.14	-	-	-	-	-	-
CV (%)	6.39	11.64	29.55	17.14	19.40	16.36	18.91	15.49	20.91	41.27	51.83

Where, P1- Application of basal nutrients only (FYMs); P2- Application of compost with basal nutrients and P3- Application of Azolla with basal nutrients, P4- Application of both compost and Azolla with basal nutrients, and C- Farmer's traditional management practice. EC- electrical conductivity, OC- organic carbon, N-nitrogen, P- phosphorus, K- potassium, Zn- Zinc, Fe- Iron, B-Boron, Ca- Calcium, Mg- magnesium. a, b, c, d, e, and f mean in columns with same superscript do not differ significantly (P< 0.05) *, LSD test. SEM: Standard Errors of Mean; CD: Critical difference; CV: Coefficient of variance

4.4.5. Yield

Rice yield data showed that the organic management strategies influenced significantly the grain yield of rice (Table 4.21). The results showed that plants under the P4 treatment produced higher yield (2494.7±76.1 kg ha^{-1}) and it was statistically significant and superior over the other treatments. It was followed by P3 treatment (2239.3±134.3 kg ha^{-1}), in which Azolla was applied with the basal nutrients. Application of compost with basal nutrients (P2), registered a grain yield of 2014.0±166.4 kg ha^{-1} and that was followed by Farmer's traditional management practices (C) C treatment (1382.0±248.3 kg ha^{-1}). The P1 treatment resulted in poor yield performance (1260.7±269.4 kg ha^{-1}).

Table 4.21. Yield of rice plant represented as Mean ± Standard Deviation (SD) of three replications.

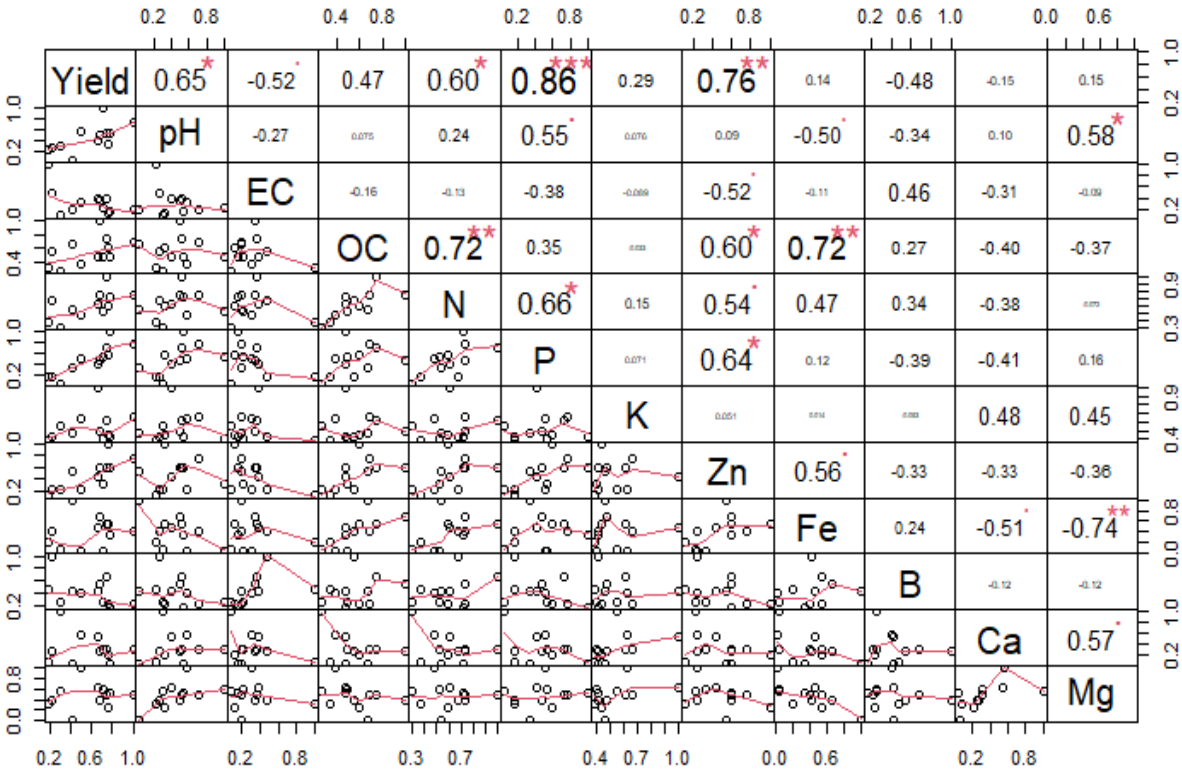
Treatments	Yield (kg ha^{-1})
P.1	1260.7±269.4c
P.2	2014.0±166.4b
P.3	2239.3±134.3ab
P.4	2494.7±76.1a
C	1382.0±248.3c
F value	*
SE(m)	162.92
CD	350.69
CV (%)	10.26

Where, P1- Application of basal nutrients only (FYMs); P2- Application of compost with basal nutrients and P3- Application of Azolla with basal nutrients, P4- Application of both compost and Azolla with basal nutrients, and C- Farmer's traditional management practices. a, b, c, d, e, and f mean in columns with same superscript do not differ significantly (P< 0.05) *, LSD test. SEM: Standard Errors of Mean; CD: Critical difference; CV: Coefficient of variance

4.4.6. Relationship study between yield and soil characters.

A simple Pearson correlation was carried out to study the relationship between yield and soil properties, specifically soil pH, electrical conductivity (EC), organic carbon content (OC), soil available nitrogen (N), phosphorus (P), potassium (K), zinc (Zn), iron (Fe), boron (B), calcium (Ca) and magnesium (Mg), respectively. The obtained data are presented in Table 4.22. Paddy yield was positively and significantly correlated with most of the soil nutrient parameters. Organic carbon and nitrogen were significantly and synergistically correlated with grain yield. Soil chemical properties such as pH (r =0.65), nitrogen (r =0.60), zinc (r=0.76) and P (r = 0.86) have a strong and positive correlation with grain yield at harvest. Organic carbon content was positively correlated with available soil nitrogen (r = 0.72).

Table 4.22. Relationship study between yield and soil characters.



Where, EC- electrical conductivity, OC- organic carbon, N-nitrogen, P- phosphorus, K-potassium, Zn- Zinc, Fe- Iron, B-Boron, Ca- Calcium, Mg- magnesium.

4.5. Experiment -5

The results acquired from the research work entitled "*Assessing the effect of different water and straw management practises on decomposition and GHG emission in post-harvest rice fields"* were collected and elucidated. This experiment was conducted in

the experimental field of IRTA, Spain as a part of the CLIFF-GRADS scholarship programme and the study was conducted to assess the different post-harvest field management to lower greenhouse gas (GHG) emissions. The treatments attempted are a) NWF ESI- Non-winter flooding with early straw incorporation; b) NWF LSI- Non-winter flooding with late straw incorporation; c) WFL ESI- Winter flooding with early straw incorporation; d) WFL LSI- Winter flooding with late straw incorporation,

4.5.1. Percentage mass loss

The results from the two-way ANOVA indicated that water management treatments and straw incorporation timing had a significant effect on the decomposition of fine litter bags/ mesh bags in the post-harvest season of 2022 and observed no interaction between them (Table.4.23). Winter flooding significantly increased the decomposition of rice straw regardless of the timing of straw input in relation to non-winter flooding.

For fine and coarse litter bags, the two-way ANOVA indicated that water management treatments and timing of straw incorporation had a significant effect on decomposition in the post-harvest season of 2022 whereas the interaction of treatments failed significantly. The percentage of mass loss under flooded conditions (WFL) was 58.75±0.76 % and 46.41±2.46 % for ESI and 54.24±1.86 % and 54.24±1.27 % for LSI, for fine and course litter bag, respectively. Whereas in non-flooded condition (NWL) percent of mass loss was 45.29±1.57 % and 26.42±1.19 % for ESI, for fine and course litter bags, respectively, and 39.20±2.79 % and 21.57±2.07 % for LSI, for fine and course litter bags, respectively. In the post-harvest season of 2022, water management significantly affects straw decomposition. Flooded (WFL) rice fields had higher litter mass loss from coarse and fine-meshed bags compared to non-flooded rice field (NFL) management. Within the winter flooding management fields, straw incorporation managements failed to affect the straw decomposition in coarse mesh bags. The late straw incorporation management field showcased reduced straw decomposition than in the early straw incorporated fields in non-flooded rice plots.

The results from the two-way ANOVA indicated that water management treatments and straw incorporation timing had no significant effect on the decomposition of fine litter bags in the growing season of 2023 and also with its interactions. The percentage of mass loss under flooded conditions was 41.28±3.28 % and 36.92±2.89 % for ESI and 43.50±2.15 % and 41.92±1.11 % for LSI, for fine and course litter bag respectively. Whereas in non-flooded condition was 39.00±3.19 % and 35.15±2.13 % for

ESI, for fine and course litter bags respectively, and 31.97±2.17 % and 29.48±1.95 % for LSI, for fine and course litter bags respectively. In the growing season, irrespective of the treatment, experimental fields were filled with water and thus water and straw incorporation timing management failed to affect the straw decomposition.

Table 4.23. Percentage mass loss fine (FIN) and coarse (COA) litter bag experiment with different water and straw management regimes

		Post harvest 2022		Growing season 2023	
		FIN	COA	FIN	COA
	NWL_ESI	45.29±1.57	26.43±1.19	62.53±2.62	35.87±9.74
	NWL_LSI	39.20±2.79	21.57±2.07	71.90±6.55	50.33±2.14
	WFL_ESI	58.75±0.76	46.41±2.46	72.00±7.64	53.70±6.99
	WFL_LSI	54.24±1.86	54.24±1.27	73.90±2.51	50.20±4.13
Irrigation	SE (m)	2.29	2.52	3.67	6.23
	CV	11.36	16.59	12.84	32.09
	P	*	*	NS	NS
Straw	SE (m)	1.14	1.07	4.53	4.58
	CV	5.65	7.05	15.83	23.63
	P	*	NS	NS	NS
Irrigation X Straw	SE (m)	1.61	1.52	-	-
	CV	11.36	16.59	-	-
	P	NS	NS	NS	NS

Where, NWF ESI- Non winter flooding with early straw incorporation; NWF LSI- Non winter flooding with late straw incorporation; WFL ESI- Winter flooding with early straw incorporation; WFL LSI- Winter flooding with late straw incorporation

4.5.2. Decomposition rate

Decomposition curves were constructed from the remaining mass of litter bags with different extraction times (Table 4.24). From decomposition curves, we identified that; straw incorporation timing and water management treatments have a significant effect on the decomposition rates of straw. An increase in percentage mass loss with increasing burial duration was observed in both coarse and fine litter bags under WFL-ESI treatment, i.e., 2.94±0.22 g and 2.09±0.07 g, respectively, for the remaining weight at extraction after 138 days of incubation. Whereas, minimum reduction in the percentage mass loss with increasing burial duration was observed in both coarse and fine litter bags under NWF-LSI treatment, i.e., 4.31±0.19 g and 3.33±0.28 g, respectively, the remain weight at extraction after 138 days of incubation.

In coarse litter bag under NWF ESI treatment, 0.17 g of mass loss was happened after the first extraction (5.28±0.15 g of mass has remained after 5 days), and 0.52 g of mass loss in second extraction (4.93±0.17 g of mass has remained after 10 days), 1.37 g in third extraction (4.08±0.13 g of mass has remained after 25 days), 1.38 g in forth extraction (4.07±0.13 g of mass has remained after 60 days) and 1.47 g in the final extraction (3.98±0.08 g of mass has remained after 138 days). In the case of fine litter bags under NWF ESI treatment, 0.54 g of mass loss was happened after first extraction(4.49±0.04 g of mass has remained after 5 days), and 0.87 g of mass loss in second extraction (4.16±0.06 g of mass has remained after 10 days), 1.96 g in third extraction (3.07±0.08 g of mass has remained after 25 days), 1.87 g in forth extraction (3.16±0.10 g of mass has remained after 60 days) and 2.27 g in final extraction (2.76±0.13 g of mass has remained after 138 days). In LSI extraction days were different from ESI. In coarse litter bag under NWF LSI treatment, 0.84 g of mass loss was happened after first extraction(4.71±0.26 g of mass has remained after 55 days), and 0.68 g of mass loss in second extraction (4.87 ± 0.15 g of mass has remained after 59 days), 0.86 g in third extraction (4.69±0.16 g of mass has remained after 66 days), 0.78 g in forth extraction (4.77±0.18 g of mass has remained after 74 days) and 1.24 g in final extraction (4.31±0.20 g of mass has remained after 138 days). In the case of fine litter bags under NWF ESI treatment, 0.56 g of mass loss was happened after first extraction(4.79±0.18 g of mass has remained after 55 days), and 0.67 g of mass loss in second extraction (4.68±0.18 g of mass has remained after 59 days), 0.90 g in third extraction (4.45±0.07 g of mass has remained after 66 days), 0.77 g in forth extraction (4.58±0.09 g of mass has remained after 74 days) and 2.02 g in final extraction (3.33±0.28 g of mass remained after 138 days).

In coarse litter bag under WFL ESI treatment, 5.33±0.02 g of mass remained after 5 days, in the second extraction 4.58±0.21 g of mass remained, 3.48±0.17 g of mass remained after 25 days, 3.37 ±0.26 g of mass remained after 60 days and 2.94±0.22 g of mass remained in final extraction. In the case of fine litter bags under NWF ESI treatment, 4.68±0.31 g of mass remained after 5 days, 3.71±0.09 g of mass loss in the second extraction, 3.04±0.09 g of mass remained after 25 days, 2.89±0.06 g of mass remained after 60 days and 2.09±0.07 g of mass remained after last extraction, i.e., 138 days. In LSI extraction days were different from ESI. In the coarse litter bag under NWF LSI treatment 3.92±0.20 g of mass remained after 55 days, and 03.81±0.24 g in final extraction, after 138 days. In the case of fine litter bags under NWF ESI treatment, 3.59±0.10 g of

remaining mass was observed after the first extraction and 2.46±0.17 g of mass remained after 138 days.

Table. 4.24. Remaining weight at extraction of fine (FIN) and coarse (COA) straw bag at six different extractions (0, 5, 10, 25, 60, 138 days for ESI and 0, 55, 59, 66, 74, 138 days for LSI)

Treatment	Total Decomposition duration (in days)	Remaining weight at extraction (g)	
		COA	FIN
NWF ESI	0	5.45±0.09	5.03±0.01
NWF ESI	5	5.28±0.15	4.49±0.04
NWF ESI	10	4.93±0.17	4.16±0.06
NWF ESI	25	4.08±0.13	3.07±0.08
NWF ESI	60	4.07±0.13	3.16±0.10
NWF ESI	138	3.98±0.08	2.76±0.13
NWF LSI	0	5.55±0.08	5.35±0.09
NWF LSI	55	4.71±0.26	4.79±0.18
NWF LSI	59	4.87±0.15	4.68±0.18
NWF LSI	66	4.69±0.16	4.45±0.07
NWF LSI	74	4.77±0.18	4.58±0.09
NWF LSI	138	4.31±0.20	3.33±0.28
WFL ESI	0	5.77±0.12	5.12±0.03
WFL ESI	5	5.33±0.02	4.68±0.31

WFL ESI	10	4.58±0.21	3.71±0.09
WFL ESI	25	3.48±0.17	3.04±0.09
WFL ESI	60	3.37±0.26	2.89±0.06
WFL ESI	138	2.94±0.22	2.09±0.07
WFL LSI	0	5.44±0.05	5.51±0.07
WFL LSI	55	3.92±0.20	3.59±0.10
WFL LSI	59	4.22±0.13	3.65±0.17
WFL LSI	66	3.89±0.17	3.18±0.15
WFL LSI	74	4.11±0.27	3.43±0.13
WFL LSI	138	3.81±0.24	2.46±0.17

Where, NWF ESI- Non winter flooding with early straw incorporation; NWF LSI- Non winter flooding with late straw incorporation; WFL ESI- Winter flooding with early straw incorporation; WFL LSI- Winter flooding with late straw incorporation

The results from the two-way ANOVA for the decomposition constant of coarse litter bags indicated that straw incorporation timing had a strong significant effect on decomposition and there was interaction between the main plot and subplot but water management treatments did not affect the decomposition rate (Table 4.25.). The results from the two-way ANOVA for the decomposition constant of fine litter bags indicated that water management treatments and straw incorporation timing had a strong significant effect on decomposition and there was no significant interaction between the main plot and subplot. The mass remaining in LSI was more than ESI irrespective of the water treatment. Also, while comparing the decomposition rate constant of each treatment, the timing of straw incorporation only influenced the decomposition rate constants in which coarse litter bags significantly affected the timing of straw incorporation treatments ($K_{WFL_ESI} > K_{NWF_ESI} > K_{WFL_LSI} > K_{NWF_LSI}$), but not in the fine litter bags ($K_{WFL_ESI} > K_{WFL_LSI} > K_{NWF_ESI} > K_{NWF_LSI}$).

Table 4.25. Statistical analysis of decomposition rate constants (k) from the fine (FIN) and coarse (COA) straw bag during the post-harvest season of 2017 under different water and straw management.

		FIN	COA
	NWL_ESI	0.0037±0.00020	0.0020±0.00013
	NWL_LSI	0.0028±0.00049	0.0011±0.00030
	WFL_ESI	0.0056±0.00022	0.0043±0.00037
	WFL_LSI	0.0038±0.00039	0.0012±0.00025
Irrigation	SE (m)	0.0002	0.0005
	CV	14.35	38.58
	P	*	NS
Straw	SE (m)	0.0002	0.0002
	CV	14.14	12.80
	P	*	*
Irrigation X Straw	SE (m)	0.0003	0.0002
	CV	14.34	12.80
	P	*	*

Where, NWF ESI- Non winter flooding with early straw incorporation; NWF LSI- Non winter flooding with late straw incorporation; WFL ESI- Winter flooding with early straw incorporation; WFL LSI- Winter flooding with late straw incorporation)

4.5.3. Methane emission

In post-harvest, the effect of water management and timing of straw incorporation strongly influenced the CH_4 emission and statistically significant, and also the interaction between straw incorporation timing and water management showed significance, resulting in increased emission rates in WFL-ESI treatment. The ranking of mean CH_4 emission rates of post-harvest season across the treatments was, from highest to lowest: 12.26±7.78 > 3.67±3.32 > 0.58±0.52 > 0.07 ± 0.26 mg CH_4- C m^{-2} h^{-1} for WFL-ESI, NFL - ESI, WFL-LSI and NWF-LSI, respectively (Table 4.26). In WFL-ESI, significant peak of

methane emissions was found immediately after the straw incorporation (16.07 mg CH_4-C m^{-2} h^{-1}). But during the same period, in the NWF- ESI plots did not have any immediate effect on methane emissions. Whereas NWF LSI treatment had the least amount of methane emissions from the post-harvest paddy field.

Table 4.26. Methane flux (mg CH_4- C m^{-2} h^{-1}) from post-harvest paddy field under different water and timing of straw incorporation management.

		Methane flux
	NWL_ESI	3.67 ± 3.32
	NWL_LSI	0.07 ± 0.26
	WFL_ESI	12.26 ± 7.78
	WFL_LSI	0.58 ± 0.52
Irrigation	SE (m)	0.65
	CV	76.78
	P	*
Straw	SE (m)	0.84
	CV	99.83
	P	*
Irrigation X Straw	SE (m)	1.19
	CV	99.28
	P	*

Where, NWF ESI- Non winter flooding with early straw incorporation; NWF LSI- Non winter flooding with late straw incorporation; WFL ESI- Winter flooding with early straw incorporation; WFL LSI- Winter flooding with late straw incorporation).

4.6. Experiment- 6

The results acquired from the research work entitled "*Calibration and validation of crop simulation model -DSSAT and temperature sensitivity analysis"* were collected and elucidated. This experiment was conducted to understand the application of the crop simulation model, DSSAT, for water and nutrient management on yield of rice under different climatic scenarios and to understand the impact of temperature on rice yield with sensitivity analysis using DSSAT model. The results of this study are detailed hereunder.

4.6.1 Calibration and Validation of Crop Simulation Model- DSSAT

To simulate rice development and yield, the DSSAT CERES-Rice model was used. The observed data comprising three stress-free treatments (P1T1, P1T2, P2T1, and P2T2) from the experiment conducted in 2019 were used to calibrate the genetic coefficients. The same treatment data for the subsequent year (2020) were used for the validation of the model. With the aid of the GENCALC tool of the DSSAT model, the genetic coefficients were established for the *Uma* rice cultivar, by performing model calculations repeatedly with multiple iterations until a significant match between model simulated and field observed phenology, growth, and yield characteristics was obtained (Table 4.27). The simulated outcomes and observed ones were contrasted in terms of correlation analysis, error percentage analysis, and other test criteria used in evaluating the model's efficacy. The following is briefly discussed:

Table 4.27. Genetic coefficients available for *Uma* rice cultivar

Coefficients	Explanations	Value
P1	Time from seed emergence to the end of juvenile phase (expressed as growing degree days (GDD) in ◦C).	698.3
P2O	Critical photoperiod or the longest day length (in hours)	12.9
P2R	extent to which phasic development leading to panicle initiation is delayed (GDD in ◦C)	130.00
P5	time period from grain filling to physical maturity (GDD in ◦C)	202.00
G1	Maximum spikelet number coefficient	74.76
G2	Maximum possible single grain weight (g) under ideal growing conditions	0.022
G3	Scalar vegetative growth coefficient for tillering relative to the IR64 tillering coefficient.	0.53
G4	Temperature tolerance is the scalar coefficient	0.906
PHINT	Phyllocron interval	83.0

4.6.1.1 Simulated versus observed - physiological maturity day

The measured and simulated number of days taken to physiological maturity day (PMD) was 99 and 97 in P1T1, 97 and 96 in P1T2, 98 and 96 in P2T1 and 92 and 95 in P2T2 during 2019, respectively. The simulated and the observed data as given in Table 4.28 revealed a deviation of – 3 to +2 days between observed and simulated days were taken to attain maturity in different treatments during 2019. The values for mean number of days taken were 96.5 & 95.5 days after planting for the simulated data and 98 & 95 days after planting for the observed data to attain maturity across different planting and N treatments during 2019. The model performance was found to be good in simulating the PDA as revealed by a high correlation coefficient, r (0.91) and low RMSE (1.58), nRMSE (0.30 %), MBE (0.5), MAPE (2.08 %), and positive D index (0.37) between the simulated and observed days taken to maturity. A good line of fit (1:1) was found between the simulated and observed data with R^2 of 0.84 during 2019 (Fig.4.10).

The observed and simulated PAD was 101 and 97 in P1T1, 95 and 96 in P1T2, 98 and 96 in P2T1 and 91 and 95 in P2T2 during 2020. The simulated and the observed data as given in Table 4.28 revealed a deviation of – 4 to + 4 days between observed and simulated days were taken to attain maturity in different treatments during 2020. The values for mean number of days taken were 96.5 & 95.5 days after planting for the simulated data and 98 & 94.5 days after planting for the observed data to attain maturity across different irrigation and N treatments during 2020. The model performance was found to be good in simulating the PAD as revealed by a high correlation coefficient, r (0.95) and low RMSE (3.04), nRMSE (0.304 %), MBE (-0.25), MAPE (2.86%), positive D index (0.32) between the simulated and observed days taken to maturity. A good line of fit (1:1) was found between the simulated and observed data with R^2 of 0.91 during 2020 (Fig. 4.10).

4.6.1.2 Simulated versus observed LAI

The measured and simulated data for leaf area index ranges from 1.98 to 2.74 and 2.43 to 2.98 in different treatments during 2019. The LAI during 2020 was 2.95 to 1.93 for the simulated data and 2.59 to 1.58 for the observed data across different irrigation and N treatments (Table 4.29). A comparison between observed and simulated values for leaf area index is presented graphically in Fig.4.10. The results revealed that simulated leaf area index matched closely with observed LAI for all the treatments. The model

performance was found to be good in simulating the leaf area index as revealed by a high correlation coefficient, r (0.92 and 0.98) and low RMSE (0.28 and 0.30), nRMSE (0.70 and 0.30 %), MBE (-0.25 and -0.29), MAPE (11.06 and 14.63 %), and positive D index (0.08 and 0.34) during 2019 and 2020, respectively, between simulated and observed data. Also, a good line of fit (1:1) was found between the simulated and observed LAI with R2 of 0.86 during 2017 and 0.96 during 2020 (Fig.4.11).

4.6.1.3 Simulated versus observed yields

The measured and simulated yield was 4851 and 4852 kg ha^{-1} in P1T1, 4307 and 4334 kg ha^{-1} in P1T2, 3714 and 3972 kg ha^{-1} in P2T1 and 3215 and 3638 kg ha^{-1} in P2T2 during 2019 (Table 4.30). The model performance was found to be good in simulating the yield as revealed by the high correlation coefficient, r (0.99) and low RMSE (248.44), nRMSE (0.15 %), MBE (-170.5), MAPE (5.32 %) and positive D index (0.8) between the simulated and observed yield. A good line of fit (1:1) was found between the simulated and observed yield with R^2 of 0.99 during 2019 (Fig.4.12).

The observed and simulated yield was 4226 and 4322 kg ha^{-1} in P1T1, 3837 and 4001 kg ha^{-1} in P1T2, 3514 and 3932 kg ha^{-1} in P2T1 and 3115 and 3494 kg ha^{-1} in P2T2 during 2020. The model performance was found to be good in simulating the yield as revealed by the high correlation coefficient, r (0.97) and low RMSE (297.69), nRMSE (0.27 %), MBE (-264.25), MAPE (27.65%), positive D index (0.47) between the simulated and observed yield. A good line of fit (1:1) was found between the simulated and observed yield with R^2 of 0.95 during 2020 (Fig.4.12).

With a high correlation coefficient and low RMSE, nRMSE, MBE and MAPE, the DSSAT-CERES model (Version 4.7) demonstrated good performance in modelling the days until physiological maturity day, LAI, and yield (Table 4.30). For maturity, leaf area index, and yield, a satisfactory line of fit was discovered between the simulated and observed data. While certain parameters were overestimated (above the line), others were underestimated, but the inaccuracy was still within allowable bounds (± 10 %). In light of this, it is practical to utilize the most recent version (V4.7) of DSSAT-CERES-Rice to simulate crop yields in Kozhikode's midland and upland regions under various planting, irrigation and N settings

Table 4.28. Statistical analysis for physiological maturity day (PMD)

	2019		2020	
	Observed	**Simulated**	**Observed**	**Simulated**
P1T1	99	97	101	97
P1T2	97	96	95	95
P2T1	98	96	98	96
P2T2	92	95	91	95
r	0.91		0.91	
R^2	0.84		0.84	
RMSE	1.58		3.00	
nRMSE	0.30		0.30	
MBE	0.50		0.50	
MAPE	2.09		2.59	
D index	0.38		0.34	

Where, P1- DSR, P2- Transplanted, T1 is 125 % of inorganic fertilizers, and T2 is 100 % of inorganic fertilizers.

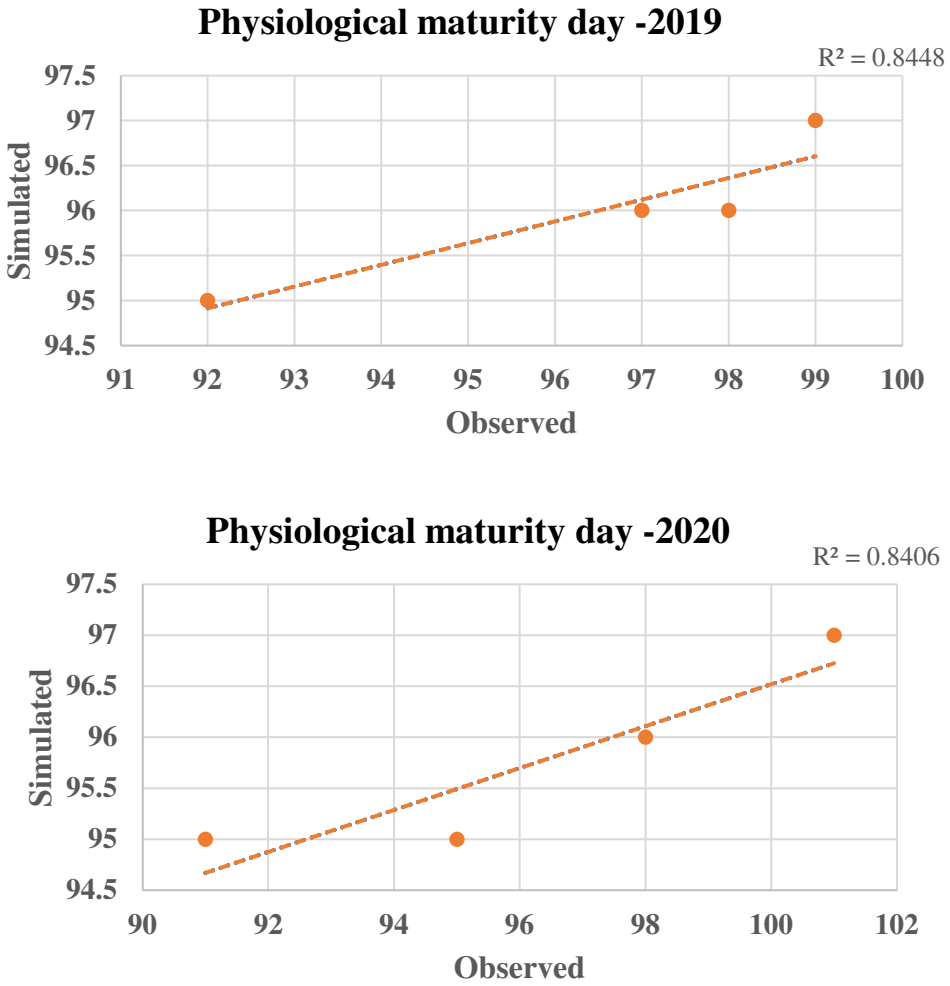


Fig.4.10. Relationship between observed and simulated physiological maturity day of rice in observed treatments in calibration (2019) and validation (2020).

Table 4.29. Statistical analysis for LAI

	2019		2020	
	Observed	**Simulated**	**Observed**	**Simulated**
P1T1	2.74	2.98	2.59	2.95
P1T2	2.34	2.55	2.34	2.52
P2T1	2.62	2.72	2.03	2.33
P2T2	1.98	2.43	1.58	1.93
r	0.93		0.98	
R^2	0.89		0.96	
RMSE	0.28		0.31	
nRMSE	0.70		0.30	
MBE	-0.25		-0.30	
MAPE	11.07		14.63	
D index	0.08		0.34	

Where, P1- DSR, P2- Transplanted, T1 is 125 % of inorganic fertilizers, and T2 is 100 % of inorganic fertilizers.

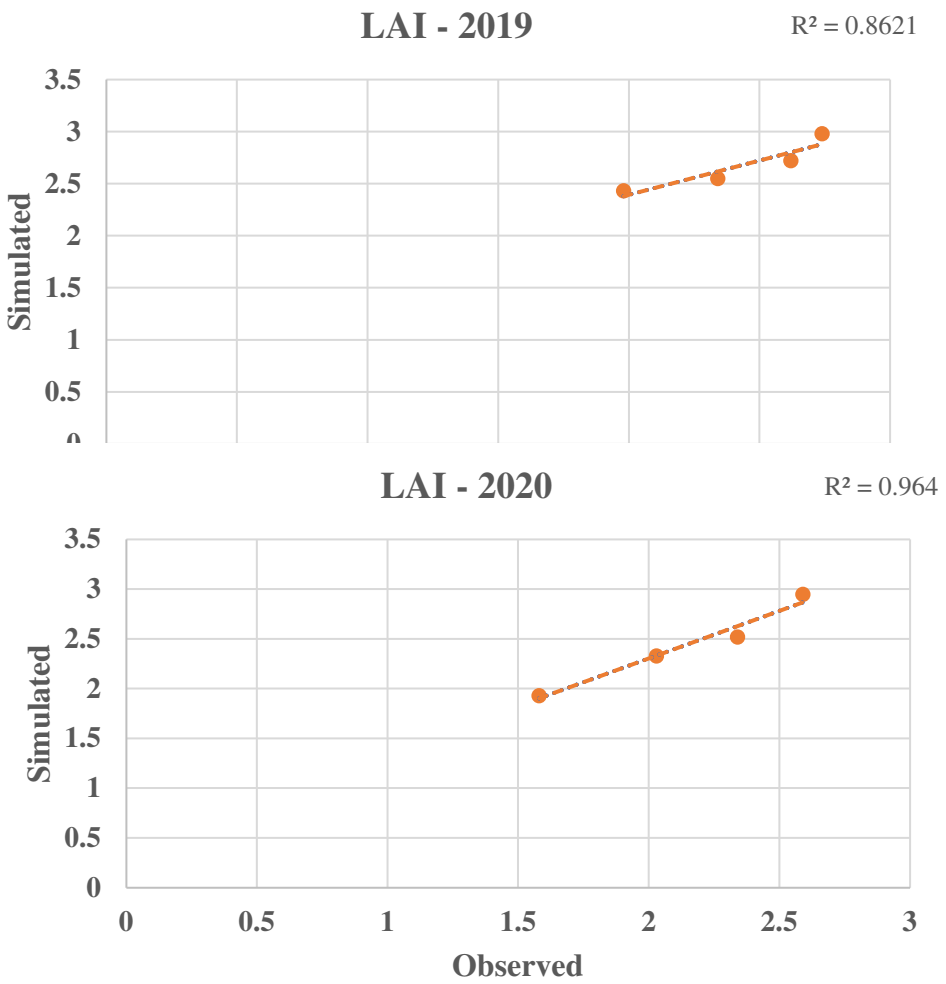
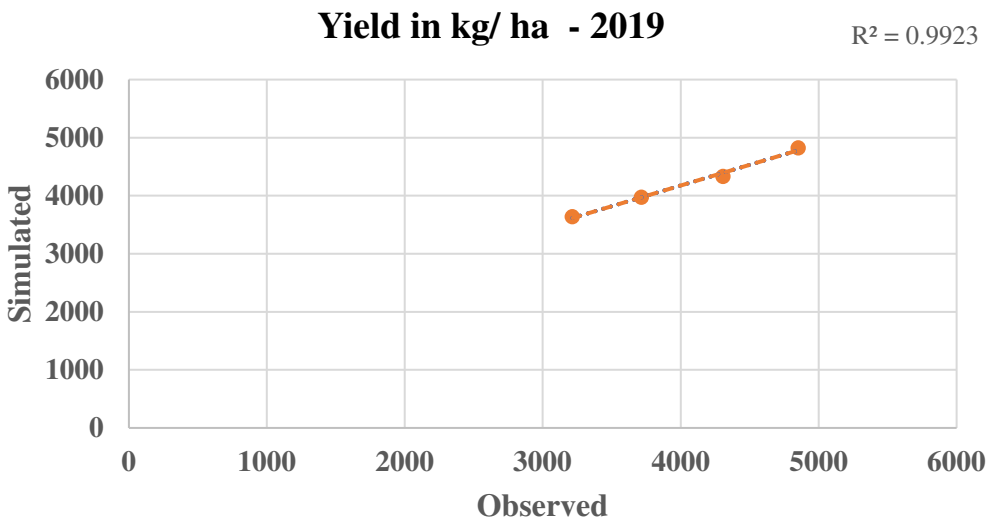


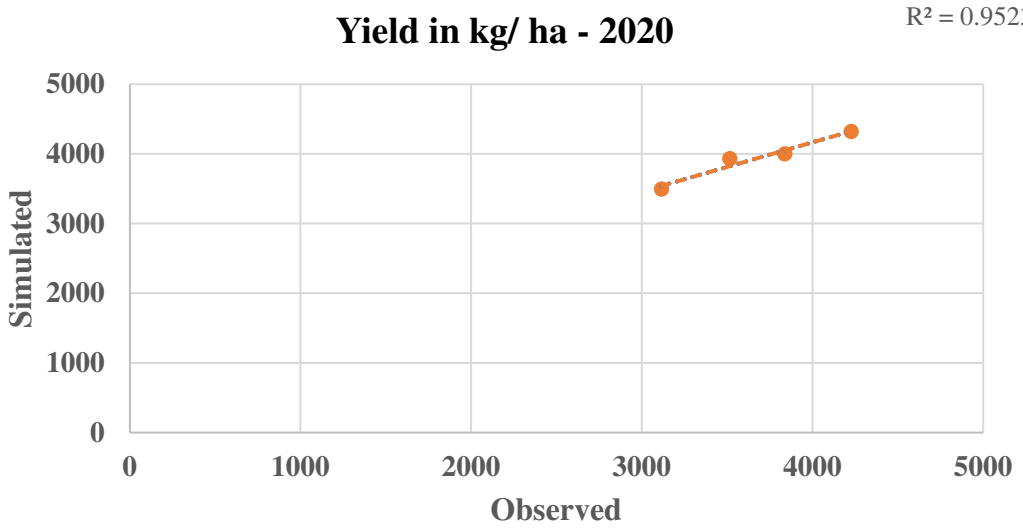
Fig.4.11. Relationship between observed and simulated leaf area index (LAI) of rice in observed treatments in calibration (2019) and validation (2020).

Table 4.30. Statistical analysis for yield in kg ha^{-1}.

	2019		2020	
	Observed	**Simulated**	**Observed**	**Simulated**
P1T1	4851	4825	4226	4322
P1T2	4307	4334	3837	4001
P2T1	3714	3972	3514	3932
P2T2	3215	3638	3115	3494
r	0.99		0.97	
R^2	0.99		0.95	
RMSE	248.444		267.69	
nRMSE	0.15		0.27	
MBE	-170.50		-264.25	
MAPE	5.32		7.65	
D index	0.83		0.47	

Where, P1- DSR, P2- Transplanted, T1 is 125 % of inorganic fertilizers, and T2 is 100 % of inorganic fertilizers.





4.6.2. Model simulation under the temperature sensitivity analysis

Paddy yield production (in kg ha^{-1}) was simulated by calibrated DSSAT software under temperature sensitivities and was compared with the simulated yield for the calibrated model for the 2019 field experiment, which was used for different methods of planting, water and nutrient management scenarios (Table 4.31). Initially, in all four treatments, rice yield was projected to increase under the scenario with a 0.5^0 C increase in both maximum and minimum temperature and under scenarios with a 1.0^0 C increase in both minimum and maximum temperature for all four treatments while comparing with the yield simulated for the 2019 experiment. A decline in the yield was predicted for scenario with 1.5^0 C increase in both minimum and maximum temperature. While comparing the yield production for various treatments under the scenario with a0.5^0 C increase in both maximum and minimum temperature, it can be seen that the treatment P1T1 gives the maximum yield (5101 kg ha^{-1}) and treatment P2T2 gives the minimum yield (3658 kg ha^{-1}). Yield predicted for the scenario with a 1.0^0 C increase in both minimum and maximum temperature for all four treatments were ranged between 4904 to 3604 kg ha^{-1}. Here, the yield of P1T1 and P1T2 experiments predicted a slight increase in the yield with the simulated yield of similar treatments in the 2019 experiment. Whereas, the yield of P2T1 and P2T2 experiments predicted a decline while comparing them with the simulated yield of the 2019 experiment. The yield predicted for P1T1 treatment under the scenarios with a1.5^0 C increase in both maximum and minimum temperature was 4039 kg ha^{-1} which is 16.3 % less than the simulated yield for P1T1 treatment in 2019 experiment. Then, it was followed by P1T2 (3526 kg ha^{-1}) with 18.6 % less yield than the simulated yield for P1T2 treatment in 2019 experiment, then for P2T1 (3083 kg ha^{-1}) with 22.4 % less yield than the simulated yield for P2T1 treatment in 2019 experiment and least predicted for P2T2 (2505 kg ha^{-1}) with 31.1 % less yield than the simulated yield for P2T2 treatment in 2019 experiment.

Rice yield predicted for scenarios with 0.5 ^{0} C, 1.0 ^{0} C and 1.5 ^{0} C increments in maximum temperatures for all four treatments showed an increase in yield when compared with the yield simulated for the 2019 experiment. Comparing the yield under different temperature increments in the P1T1 treatment, the highest was predicted for the scenario with 1.0 ^{0} C increments in maximum temperatures (5178 kg ha^{-1}) and was followed by the scenario with 1.5 ^{0} C increments in maximum temperatures (5060 kg ha^{-1}) and least yield was predicted for the scenario with 0.5 ^{0} C increments in maximum temperatures (4664 kg

ha^{-1}). The yield difference among the temperature sensitivity analysis for P1T2 treatment also showed a similar trend to P1T1 treatment and it yield ranges from 4501 to 4296 kg ha^{-1}. In P2T1 treatment, the highest yield was predicted for the scenario with a 0.5 ^{0} C increments in maximum temperatures (3983 kg ha^{-1}) and is followed by the scenario with a 1.0 ^{0} C increments in maximum temperatures (3969 kg ha^{-1}) and the least for the scenario with a 1.5 ^{0} C increments in maximum temperatures (3963 kg ha^{-1}). The yield predicted for different scenarios of temperature increments in P2T2 treatment have less variations and was 3666 $\pm$ 8.34 kg ha^{-1}.

Rice yield predicted for scenarios with 0. 5^0 C, 1.0 ^{0} C and 1.5 ^{0} C increments in minimum temperatures for all four treatments showed sequential increase in yield when comparing with the yield simulated for the 2019 experiment. In P1T1 treatment, highest yield prediction was found in the scenario with a 1.5 ^{0} C increments in minimum temperatures (5178 kg ha^{-1} with 5.64 % increment and least yield prediction was found in the scenario with a 0.5 ^{0} C increments in minimum temperatures (5080 kg ha^{-1}) with 5.28 % increment than the simulated yield for P1T1 treatment in 2019 experiment. The same trend was observed for P1T2 and P2T2 treatments too. In P2T1 treatment, yield predicted for the scenario with 0.5 ^{0} C and 1.0 ^{0} C increments in minimum temperatures had a decline in production to 3958 kg ha^{-1} and 3969 kg ha^{-1}, respectively, from 3972 kg ha^{-1} of simulated yield for P2T1 treatment in 2019 experiment.

Table 4.31. Yield production simulations under temperature sensitivity analysis

	2019 simulated (kg ha^{-1})	**0.5 ^{0}C increase in Tmax & Tmin** (kg ha^{-1})	**1.0 ^{0}C increase in Tmax & Tmin** (kg ha^{-1})	**1.5 ^{0}C increase in Tmax & Tmin** (kg ha^{-1})
P1T1	4825	5101	4904	4039
P1T2	4334	4567	4406	3526
P2T1	3972	3973	3965	3083
P2T2	3638	3658	3604	2505
	2019 simulated (kg ha^{-1})	**0.5 ^{0}C increase in Tmax** (kg ha^{-1})	**1.0 ^{0}C increase in Tmax** (kg ha^{-1})	**1.5 ^{0}C increase in Tmax** (kg ha^{-1})
P1T1	4825	4664	5178	5060
P1T2	4334	4296	4501	4445
P2T1	3972	3983	3969	3963
P2T2	3638	3693	3678	3655
	2019 simulated (kg ha^{-1})	**0.5 ^{0}C increase in Tmin** (kg ha^{-1})	**1.0 ^{0}C increase in Tmin** (kg ha^{-1})	**1.5 ^{0}C increase in Tmin** (kg ha^{-1})
P1T1	4825	5080	5097	5178
P1T2	4334	4529	4601	4686
P2T1	3972	3958	3969	4084
P2T2	3638	3650	3678	3698

Where, P1- DSR, P2- Transplanted, T1 is 125 % of inorganic fertilizers, and T2 is 100 % of inorganic fertilizers.

4.7. Experiment -7

The results acquired from the research work entitled "*Suitability analysis and rice yield prediction for Kozhikode and Palakkad districts under future climate scenarios"* were collected and elucidated.

This experiment was conducted to explore the potential areas for rice production through suitability analysis and yield predictions for Kozhikode district as well as Palakkad district under future climate scenarios. Even though all the field experiments were carried out in Kozhikode district, Palakkad district is one of the main paddy growing districts in Kerala. However, the sustainability of paddy agriculture in the area is seriously threatened by the changing patterns of the climate, which include rising temperatures, altered rainfall patterns, and an increase in the frequency of extreme weather events. Which negatively impacts the paddy production. In order to address this problem, a study was carried out to determine viable adaptation strategies and to evaluate the prospective effects of climate change on paddy production in the Kozhikode and Palakkad areas.

4.7.1 Crop Suitability for Paddy Cultivation in Kozhikode

4.7.1.1. THEMATIC MAPS

The thematic maps displayed above in Fig.4.13, Fig.4.14 and Fig.4.15 shows the distribution of Photosynthetically Active Radiation (PAR), Fraction of Absorbed Photosynthetically Active Radiation (fAPAR), and Water Stress in Kozhikode district. The high average value of PAR for paddy in the Kozhikode district is 379.176 MJm^{-2} and the minimum low value is 319.236 MJm^{-2}. The fAPAR value is a real-time indicator of crop growth conditions during the growing season and varies depending on the ecosystem and time. In this study, the fAPAR value ranged from 0.05 to 2.54. The water stress during the season was optimal for paddy growth, prolonged water stress can negatively affect crop growth and productivity.

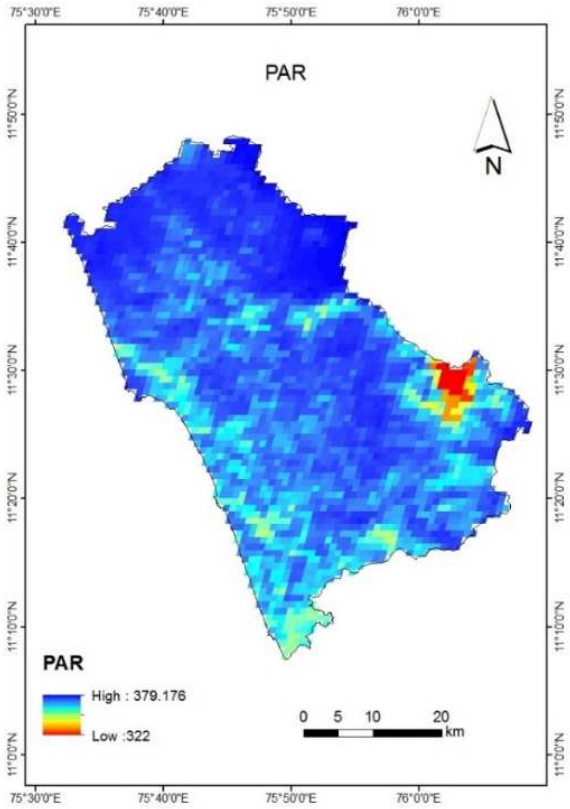


Fig.4.13. PAR Map of Kozhikode district

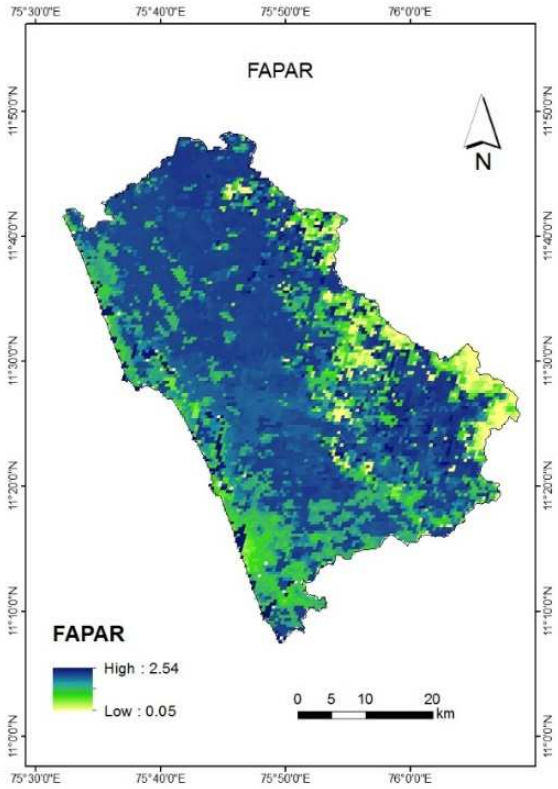


Fig.4.14. fAPAR Map Kozhikode district

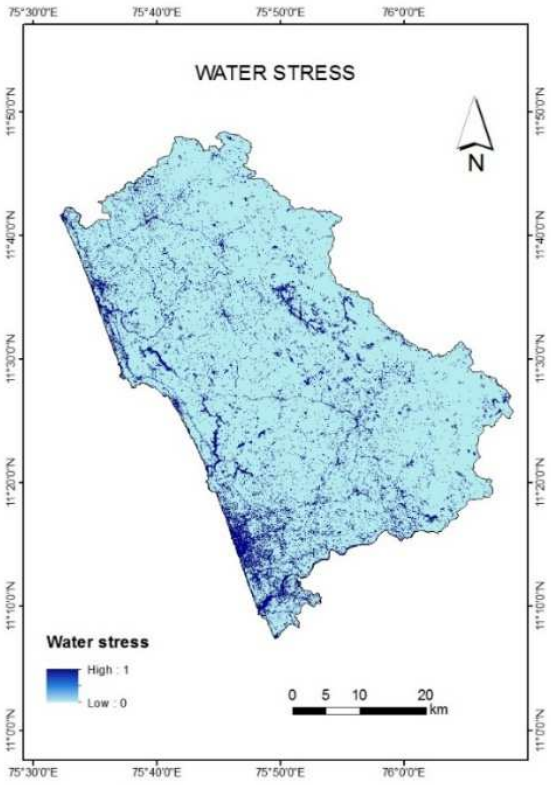


Fig.4.15. Water Stress Map Kozhikode district

4.7.1.2. AHP Table

The table 4.32 displays a pair-wise comparison of alternatives based on certain criteria, using the AHP method. By assigning weights to the criteria, the AHP approach provides a more systematic and rational decision-making process. If the consistency ratio is less than or equal to 0.1, the pairwise comparisons are considered to be reasonably consistent. However, if the ratio exceeds 0.1, the decision maker may need to reassess their judgments and revise the matrix to improve its consistency. In our case, the calculated consistency index from the AHP table above is 0.10, indicating that the pairwise comparisons are reasonably consistent.

Table 4.32. Pairwise comparison table for paddy suitability of Kozhikode district

	Rainfall	**pH**	**Texture**	**Temperature**	**Drainage**	**Depth**	**Slope**
Rainfall	1	5	3	3	7	5	7
pH	0.2	1	1	3	5	3	5
Texture	0.3	1	1	3	5	3	5
Temperature	0.3	0.3	0.3	1	3	3	3
Drainage	0.1	0.2	0.2	0.3	1	3	3
Depth	0.2	0.3	0.3	0.3	0.3	1	3
Slope	0.1	0.2	0.2	0.3	0.3	0.3	1
Total	2.4	8.1	6.1	11	21.7	18.3	27

4.7.1.3. Factors Influencing Paddy's Suitability

The factors that can influence the suitability of paddy cultivation in the district are rainfall, pH of soil, soil texture, temperature, soil drainage, soil depth, and slope. Based on the table (Table 4.33), it appears that rainfall has a significant influence on paddy suitability in the Kozhikode district with 38 % weightage. This is followed by soil texture, pH, temperature, drainage and depth, 18 % ,17 %, 11 %, 7 %, and 6 % weightage respectively. Slope has the least influence on paddy suitability (3 %).

Table 4.33. Influence table for paddy suitability of Kozhikode district

Raster	Weightage (%)
Rainfall	38
Texture	18
pH	17
Temperature	11
Drainage	7
Depth	6
Slope	3

4.7.1.4. Paddy suitability

The results of the suitability map indicate that half of the land in the Kozhikode district is suitable for paddy cultivation. This information is useful for farmers, policymakers, and other stakeholders in the agricultural sector, as it can help guide decisions related to agricultural planning, resource allocation and land use. Furthermore, Fig.4.16 shows that the regions of Thodannur, Melady and Perambra in the Kozhikode district is highly favourable for growing paddy, accounting for a total of 3 % of the highly suitable area for paddy cultivation in the district. Forty-five per cent of the Kozhikode district area is moderately suitable for paddy cultivation and this region belongs to the midland region. The remaining area is classified as either not suitable (21 %) or marginally suitable (30 %) due to environmental and soil factors that do not support rice cultivation.

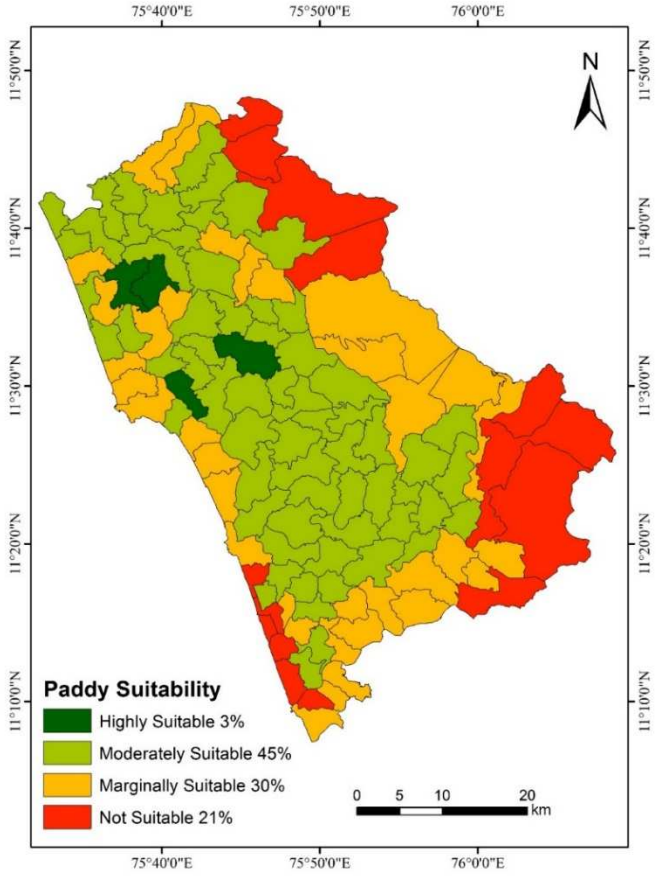


Fig.4.16. Suitability map for paddy cultivation in Kozhikode district

4.7.2. Yield estimation

4.7.2.1. Current scenario

Based on the annual paddy yield map results for the current scenario, the Koduvally block in the Kozhikode district had a higher estimated yield for paddy at 2848 kg ha^{-1}, while the Kunnummal block had a lower estimated yield at 1525 kg ha^{-1} (Fig.17). The predicted yield was also found to be comparable to the observed yield data from Department of economics and statistics (DoES).

It is crucial to note that yield predictions might vary depending on a number of variables, including the weather, the quality of the soil, irrigation methods, and crop management strategies. As a result, yield estimates for paddy in various blocks will probably change from season to season, and care should be taken before concluding data collected in a single growing season.

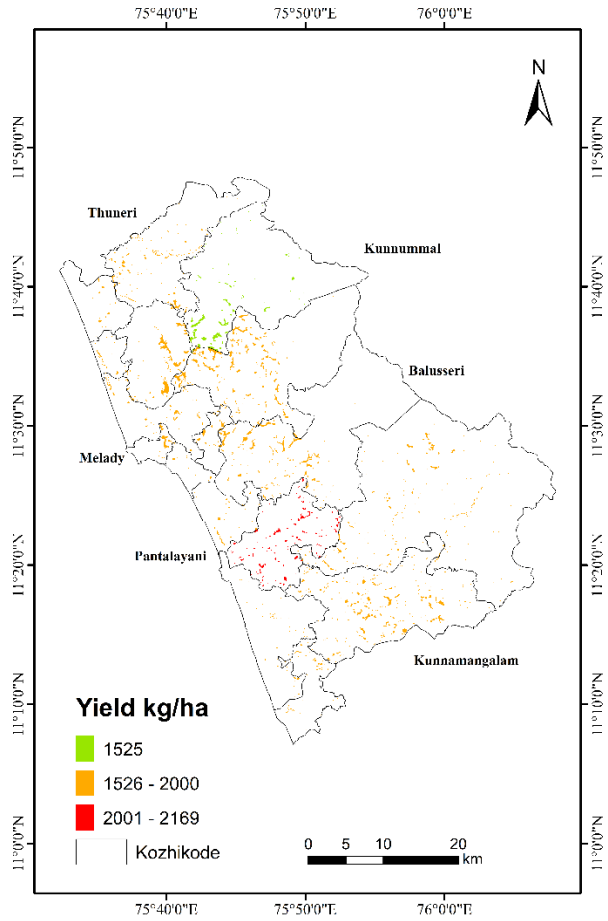


Fig.4.17. Map for current paddy production in Kozhikode district

Moreover, yield estimates should be used in conjunction with other information sources and local expertise to make well-informed decisions about agricultural planning and land use, even though they are a useful tool for understanding agricultural productivity and making decisions about crop selection and resource allocation.

4.7.2.2. Future Scenario

The temperature data of Kozhikode district for the years 2025, 2050, 2100, which includes Tmax and Tmin of four climate models (CMCC-ESM2, EC-Earth3, EC-Earth3-Veg, and GFDL-CM4) were collected for analysing the future scenario. These temperature data were obtained from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) for both SSP245 and SSP585 Scenario. From the temperature data we obtained it is found that temperature is expected to increase from 2025 to 2100 (Table 4.34). Here we are utilizing the temperature data for our study to estimate the production. We estimated

the future paddy yields for each model under both the SSP245 and SSP585 scenarios, and analysed the corresponding projected climate changes.

Table 4.34. Table of Temperature Data of Models

		Avg Max Temperature(ºC)				**Avg Min Temperature(ºC)**			
MODEL	**Scenario**	2023	2025	2050	2100	2023	2025	2050	2100
CMCC-ESM2	245	28	29	30	31	21	19	20	21
	585		29	31	33		19	21	24
EC-EARTH3 VEG	245	29	30	30	30	18	20	21	21
	585		29	31	33		20	22	25
GFDL-CM4	245	27	30	30	31	25	20	21	21
	585		29	30	32		19	21	23
EC- EARTH 3	245	29	30	31	31	17	20	21	21
	585		30	31	33		20	21	25

Based on the analysis conducted using four climate models (CMCC-ESM2, EC-Earth3, EC-Earth3-Veg, and GFDL-CM4) and considering the SSP 245 and SSP 585 scenarios, it has been observed that there is a projected decrease in paddy yield in Kozhikode district as the year's progress from 2025 to 2100. The analysis was based on the map provided in figures – Fig.4.18 – Fig.4.21. In CNCC and EC EARTH 3 models predicted decrease in the productivity by the change in colour on the map provided below, where the transition from red to green represents a decline in yield due to increasing temperatures. Maps created for the CMCC SSP 2-4.5 show that as years went from 2025 to 20100, the red areas with high productivity tended to persist that way, while the orange parts changed to green as a sign of declining productivity (15.30 %). In the CMCC SSP 5-8.5, by the year 2100, rice productivity had significantly decreased (726 kg ha^{-1}), and all regions' colours had changed to green on the map and a lack of other colours signifying the decreased productivity. The rice productivity of Kozhikode district was predicted by EC EARTH VEG and GFDL models to increase in future scenarios (both in SSP 2- 4.5 and 4- 8.5). This was indicated by a change in colour on the map below, where a large

distribution of red-orange colours and a complete reduction of green colour indicated an increase in yield due to rising temperatures by the year 2100.

4.7.2.3. Estimated Yield OF MODELS CMIP6-SSP245 & SSP585

The estimated block wise yield of Kozhikode for four different climate models under the SSP245 and SSP585 scenario. For the model EC-EARTH VEG, there is a decrease in the yield from 2025 to 2099 on every blocks. In the case of SSP245 scenario its observed that slight increase (27.44 %) in production of paddy from 2025 to 2050 and then predicted a decrease from 2050 to 2099 by 24.84 %, overall, the average decrease in yield from 2025 to 2099 is less (4.21 %). The SSP 585 graph shows a significant increment (27.88 %) in yield through years (2025 to 2100), when compared to the SSP 245, which accounts to an 1.79 % in production predictions from the year 2025 to 2050, 25.73 % increment from 2050 to 2100. Similarly, the GFDL-CM4 model for SSP 585 scenario is also showing an increase of 13.25 % in the yield from 2025 to 2099. The SSP245 scenario graph shows a minor decrease in the yield which accounts to an average 98.5 T and 154.10 T decrease in the year 2025 and 2100, respectively. While, in SSP585 graph every block shows a continuous increase in yield through the years, except the block Melady in which the yield is decreased by 153.30 T in the year 2100 when compared to 2025. The average increase of yield from 2025 to 2099 in Kozhikode district is accounts to 13.25 % in SSP585 scenario for GFDL model.

For CMCC-ESM2 model, the SSP 245 scenario estimated an average of 577.30 T of production is decreased from 2025 to 2050 and after that in 2100, 714.70 T production is decrease from 2050 in paddy production. In SSP 585 scenario graph it's sharp decline of 68.31 % in the paddy production from 2025 to 2100. The predicted production for the year 2025 is 2476.6. T, and for 2050 is 1062.9 T (57.08 % reduction) and for the year 2100 is 784.8 T. For the model EC-EARTH 3, the graph of SSP 245 scenario shows the paddy production in the various blocks in Kozhikode districts have a reduction of 88.33 T from the year 2025 to 2050 and, then followed increment of 14.67 % in the year 2100. The EC EARTH 3 model's SSP 585 scenario displays a decline of 26.14 % production in each forecast year from 2025 to 2100 through 2050.

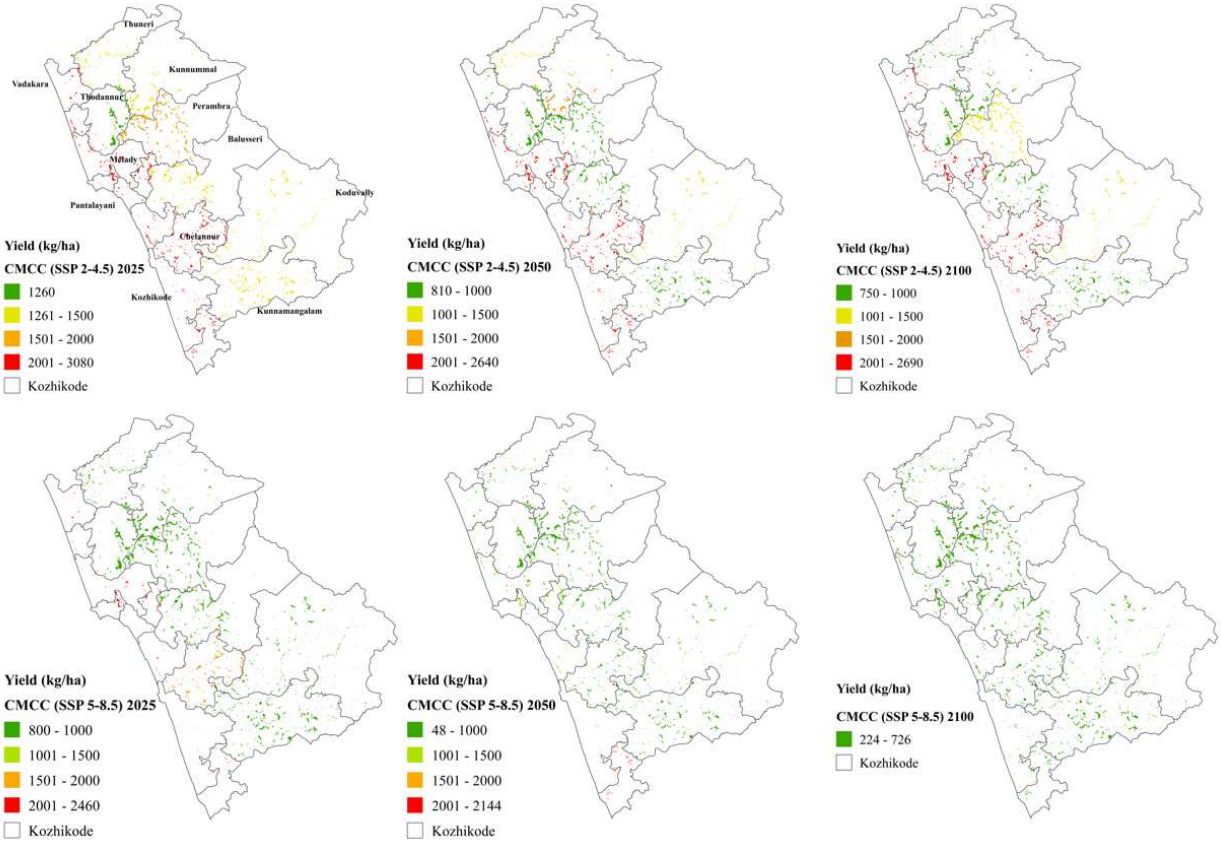


Fig.4.18. Kozhikode- Estimated yield for the model CMCC-ESM2

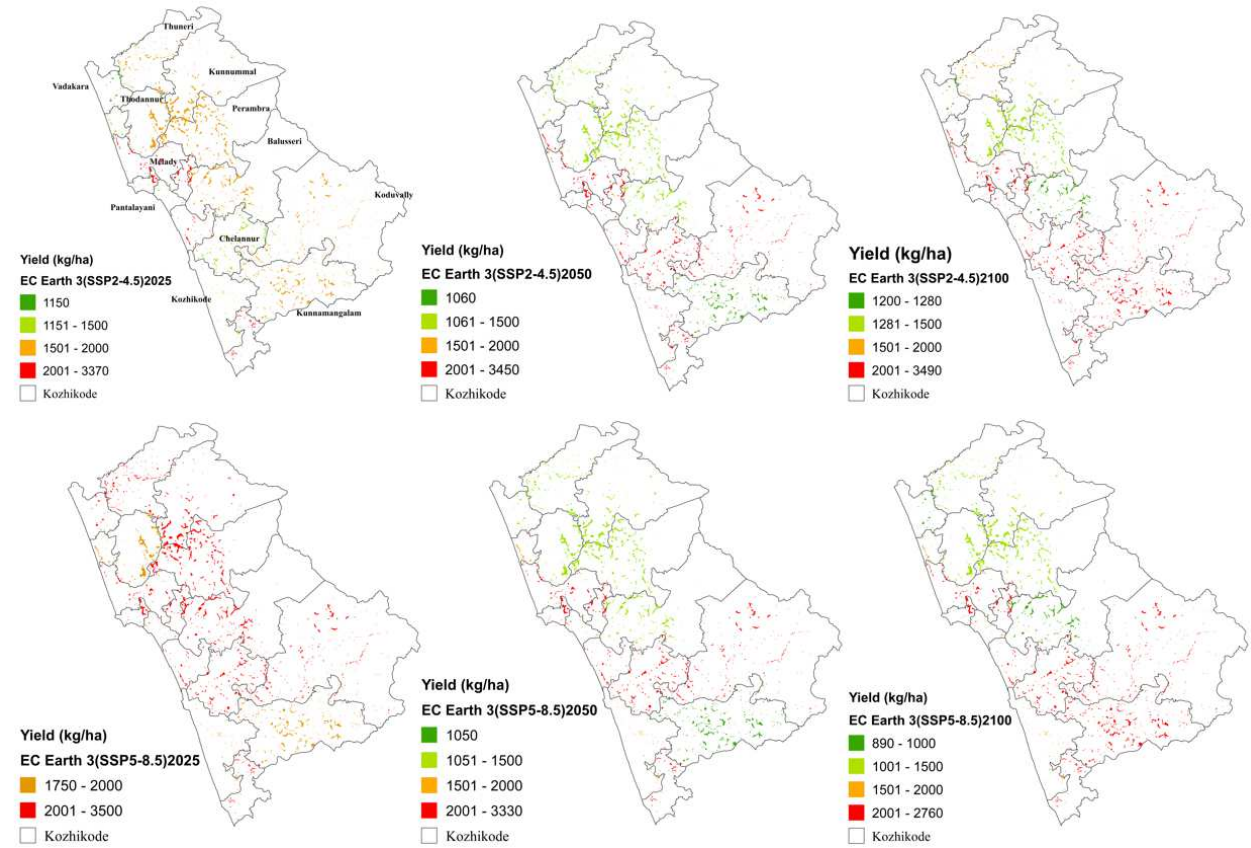


Fig.4.19. Kozhikode- Estimated yield for the model EC EARTH-3

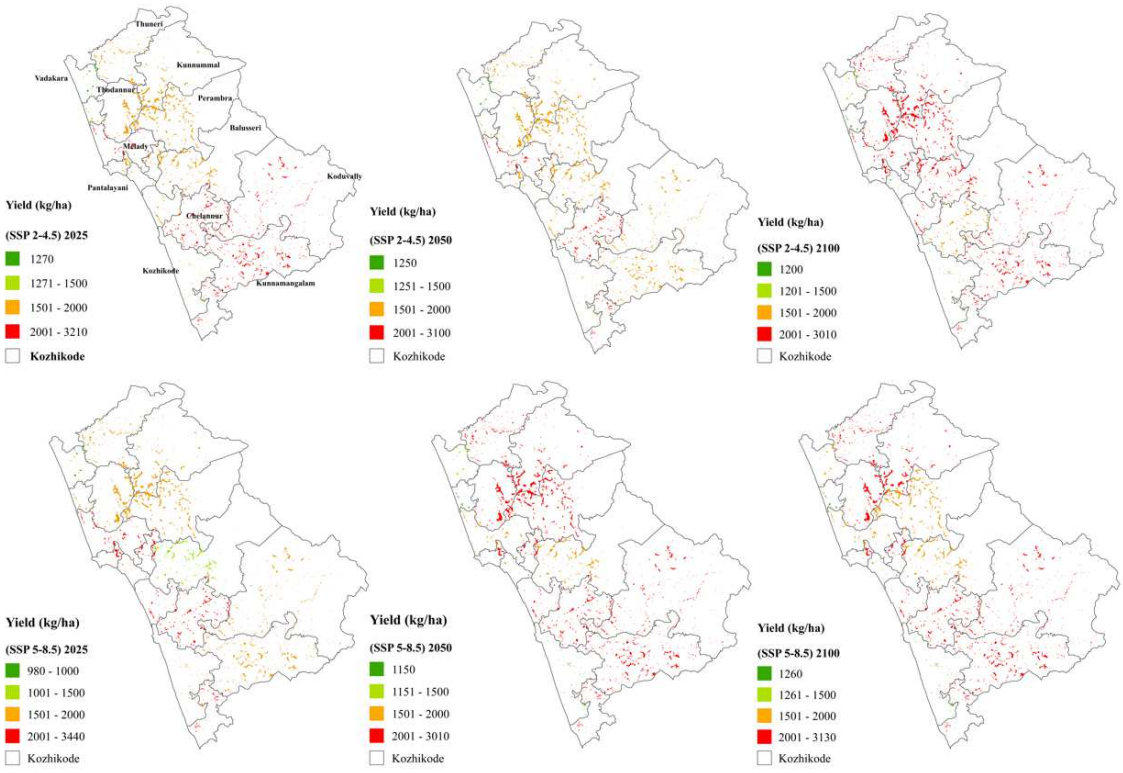


Fig.4.20. Kozhikode- Estimated yield for the model EC EARTH- VEG

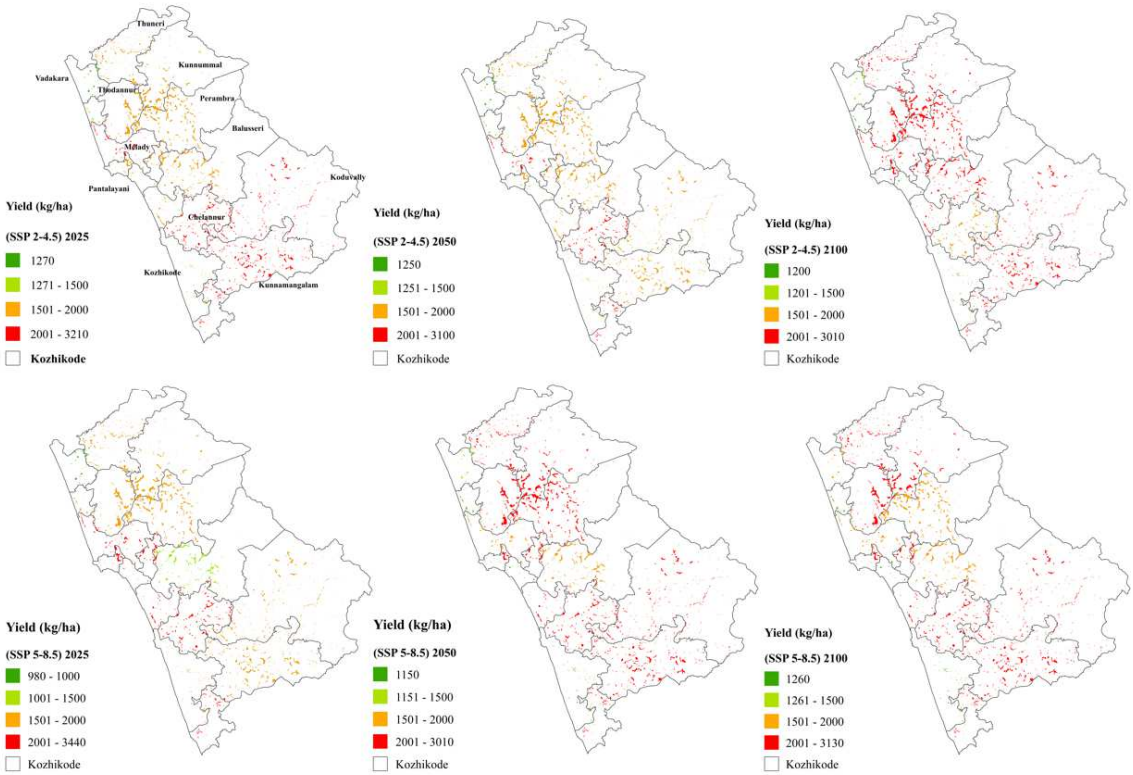


Fig.4.21. Kozhikode- Estimated yield for the model GFDL-CM4

4.7.3. Crop Suitability for Paddy Cultivation in Palakkad

4.7.3.1. THEMATIC MAPS

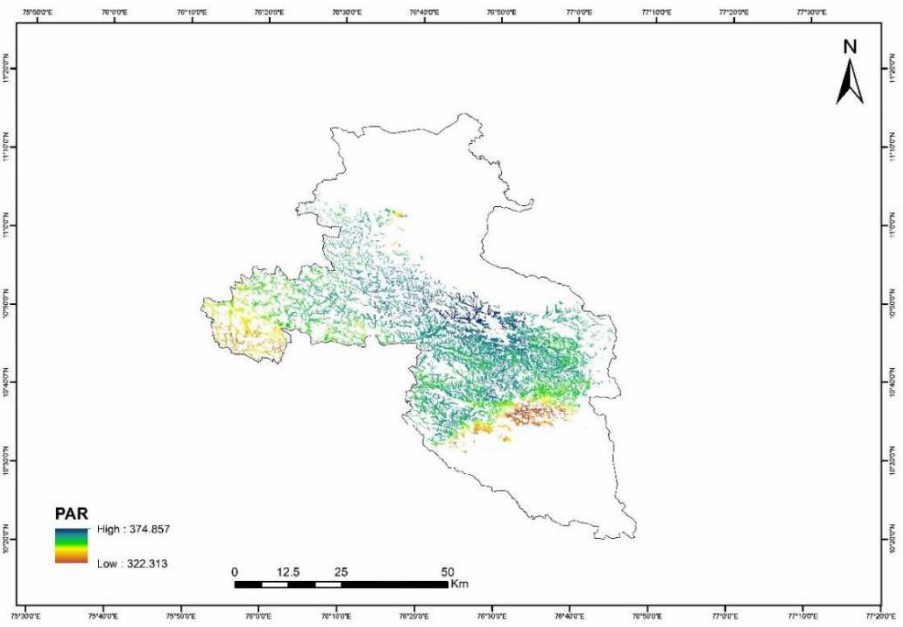


Fig.4.22. PAR Map of Palakkad district

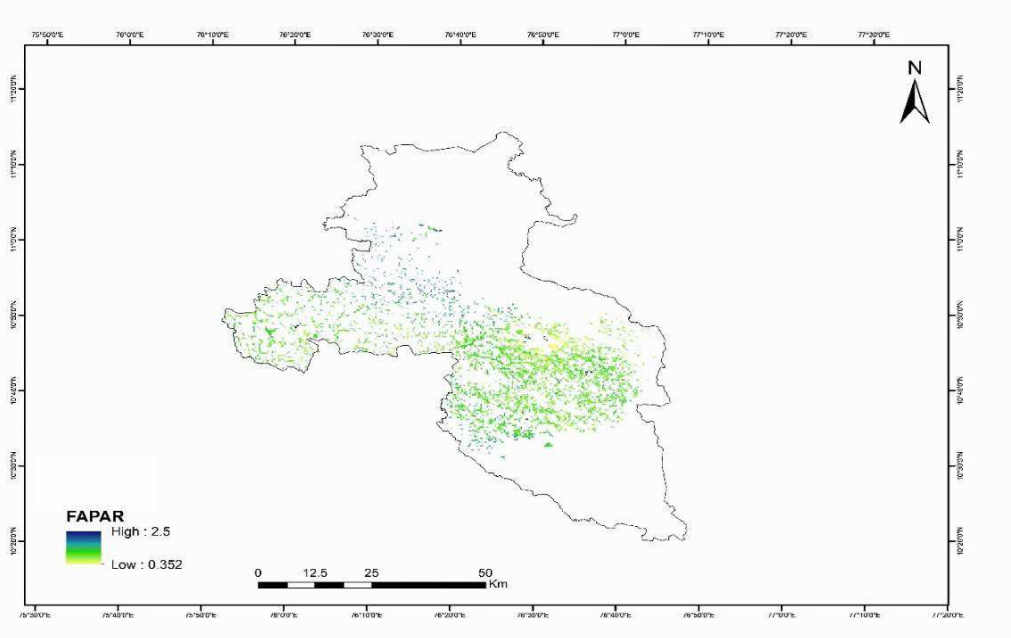


Fig.4.23. fAPAR Map of Palakkad district

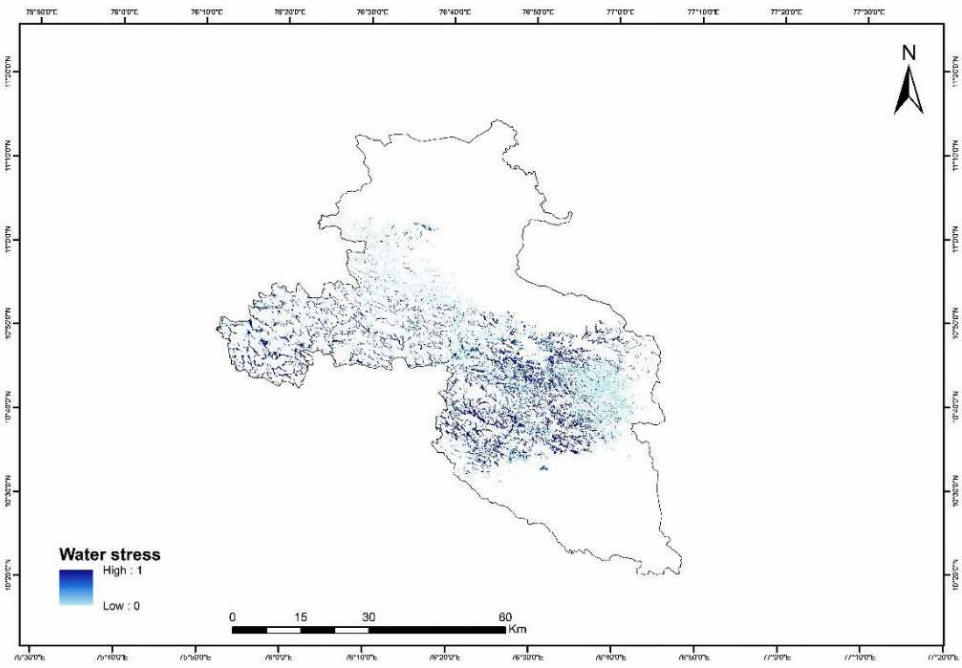


Fig.4.24. Water Stress Map of Palakkad district

The thematic maps displayed above in Fig.4.22, Fig.4.23 and Fig.4.24 shows the distribution of Photosynthetically Active Radiation (PAR), Fraction of Absorbed Photosynthetically Active Radiation (fAPAR), and Water Stress in Palakkad district. The high average value of PAR for paddy in the Palakkad district is 374.88 MJm^{-2} and the minimum low value is 322.31 MJm^{-2}. The fAPAR value is a real-time indicator of crop growth conditions during the growing season and varies depending on the ecosystem and time. In this study, the fAPAR value ranged from 0.35 to 2.5. The water stress during the season was optimal for paddy growth, prolonged water stress can negatively affect crop growth and productivity.

4.7.3.2. AHP Table

The table 4.35 displays a pairwise comparison of alternatives based on certain criteria, using the AHP method. By assigning weights to the criteria, the AHP approach provides a more systematic and rational decision-making process. If the consistency ratio is less than or equal to 0.1, the pairwise comparisons are considered to be reasonably consistent. However, if the ratio exceeds 0.1, the decision maker may need to reassess their judgments and revise the matrix to improve its consistency. In our case, the calculated

consistency index from the AHP table above is 0.067, indicating that the pairwise comparisons are reasonably consistent.

Table 4.35. Pairwise comparison table for paddy suitability of Palakkad district

	Rainfall	**Slope**	**Depth**	**Drainage**	**Calcium carbonate**	**pH**	**Temperature**	**Texture**
Rainfall	1	5	7	5	6	5	4	8
Slope	0.2	1	5	2	3	5	3	5
Depth	0.14	0.2	1	9	3	3	6	7
Drainage	0.2	0.5	0.11	1	4	5	5	8
Calcium carbonate	0.17	0.33	0.33	0.25	1	5	3	3
pH	0.2	0.2	0.33	0.2	0.2	1	4	7
Temperature	0.25	0.33	0.167	0.2	0.33	0.25	1	4
Texture	0.125	0.2	0.142	0.125	0.33	0.147	0.25	1
Total	2.16	7.57	13.94	17.65	17.53	24.25	26	43

4.7.3.3. Factors Influencing Paddy's Suitability

The factors that can influence the suitability of paddy cultivation in the Palakkad district are rainfall, pH of soil, soil texture, temperature, soil drainage, soil depth, and slope. Based on the table (Table 4.36), it appears that texture has a significant influence on paddy suitability in the Palakkad district with 35 % weightage. Which is followed by slope, pH, temperature, drainage, rainfall, depth and calcium carbonate, 17 % ,16 %, 13 %, 7 %, 6 %, 4 % and 2 % weightage respectively. Calcium carbonate has the least influence on paddy suitability.

Table 4.36. Influence table for paddy suitability of Kozhikode district

Raster	Weightage (%)
Texture	35
Slope	17
pH	16
Temperature	13
Drainage	7
Rainfall	6
Depth	4
Calcium carbonate	2

4.7.3.4. Paddy suitability

The results of the suitability map indicate that large portion of the land in the Palakkad district is suitable for paddy cultivation. This information is useful for farmers, policymakers, and other stakeholders in the agricultural sector, as it can help guide decisions related to agricultural planning, resource allocation, and land use. Furthermore, Fig.4.25 shows that the region of Pattambi in the Palakkad district is highly favourable for growing paddy, accounting for 2.12 % of the highly suitable area for paddy cultivation in the district. Ninety-six percentage of the Palakkad district area is moderately suitable for paddy cultivation and this region. The remaining area is classified as either not suitable (1.36 %) or marginally suitable (0.86 %) due to environmental and soil factors that do not support rice cultivation.

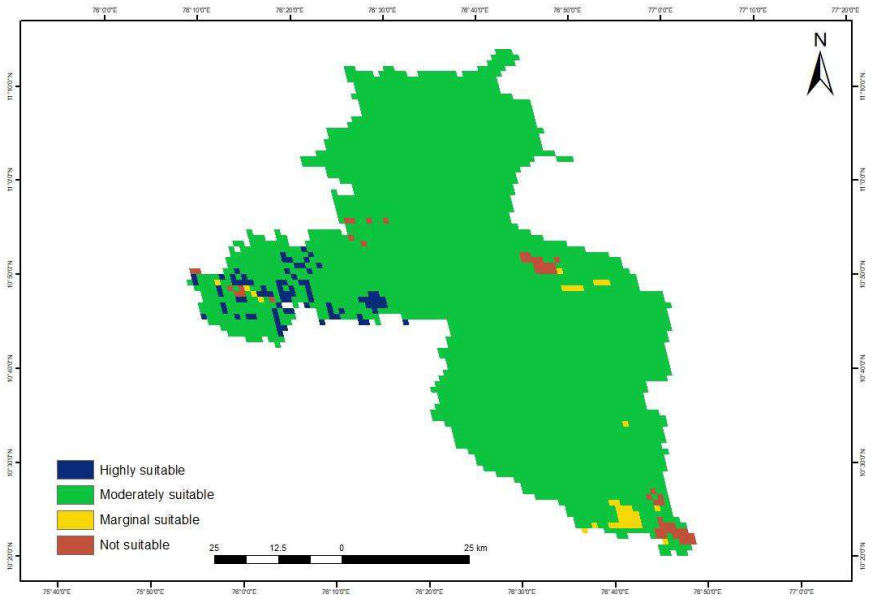


Fig.4.25. Suitability map for paddy cultivation in Palakkad district

4.7.4. Yield estimation

4.7.4.1 Current scenario

Based on the seasonal paddy yield map results for current scenario, it can be concluded that during the Mundakkan season of paddy in the year 2020, Ottapalam taluk in the Palakkad district had a higher estimated yield for paddy at 2130 kg ha^{-1}, while Chittur taluk had a lower estimated yield at 1818 kg ha^{-1} (Fig.4.26). The predicted yield was also found to be comparable to the observed yield data from DoES. Therefore, it can be inferred that among the six taluks in the Palakkad district, Ottapalam taluk had a higher rice production during that season.

However, it is important to note that yield estimates are subject to various factors such as weather conditions, soil quality, irrigation practices, and crop management techniques. Therefore, it is possible that the yield estimates for paddy in different taluks may vary from season to season, and caution should be exercised when drawing conclusions based on data from a single season. Furthermore, while yield estimates are a useful tool for understanding agricultural productivity and making decisions related to crop selection and resource allocation, they should be used in conjunction with other sources of information and local expertise to make informed decisions about agricultural planning and land use.

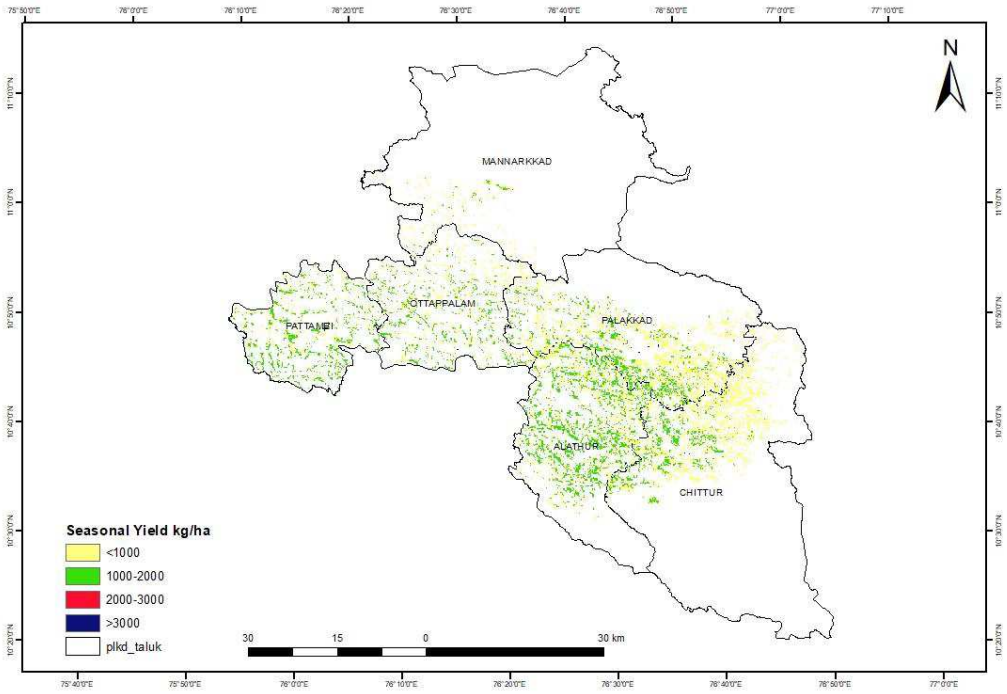


Fig.4.26. Map for current paddy production in Palakkad district

4.7.4.2. Future Scenario

The temperature data of Palakkad district for the years 2025, 2050, 2075, and 2100, of four climate models were used for analysing the future scenario. These temperature data were obtained from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) for both SSP 2–4.5 and SSP 5-8.5 Scenario. From the temperature data we obtained it is found that temperature is expected to increase from 2025 to 2100. Here we are utilizing the temperature data for our study to estimate the production. We estimated the future paddy yields for each model under both the SSP 2-4.5 and SSP 5-8.5 scenarios, and analysed the corresponding projected climate changes.

Based on the analysis conducted using four climate models (CMCC-ESM2, EC-Earth3, EC-Earth3-Veg, and GFDL-CM4) and considering the SSP 245 and SSP 585 scenarios, it has been observed that there is a projected decrease in paddy yield in Palakkad district as the year's progress from 2025 to 2100. The analysis was based on the map provided in figures – Fig.4.27 – Fig.4.30. The map's colour shift from yellow to a darker blue signifies a drop in yield as a result of temperature. Thus, it may be said that from 2025 to 2100, the Palakkad district's agriculture yield would decline due to temperature increases. In all four models predicted decrease in the productivity by the change in colour on the map provided below, where the transition from yellow to dark blue represents a decline in yield due to increasing temperatures.

4.7.4.3. Estimated Yield OF MODELS CMIP6-SSP245 & SSP585

The yields for four different crop models under the SSP245 scenario are simulated. For the CMCC model, the average yield decreases from 2029 kg ha^{-1} in 2025 to 919 kg ha^{-1} in 2100. Similarly, the EC EARTH3 model shows a decrease from 2131 kg ha^{-1} to 1043 kg ha^{-1}, and the EC EARTH-VEG model from 2591 kg ha^{-1} to 910 kg ha^{-1}. The GFDL-CM4 model also shows a decline from 2334 kg ha^{-1} to 791 kg ha^{-1}, while the GFDL-ESM4 model decreases from 2994 kg ha^{-1} to 871 kg ha^{-1}. In conclusion, we can infer that the crop yield decreases with increasing temperature when analyzing data from 2020 to 2100.

The yields for five different crop models under the SSP585 scenario are simulated. For the CMCC model, the average yield decreases from 1964 kg ha^{-1} in 2025 to 696 kg ha^{-1} in 2100. Similarly, the EC EARTH3 model exhibits a decrease from 2119 kg ha^{-1} to 747 kg ha^{-1}, and the EC EARTH-VEG model from 1969 kg ha^{-1} to 726 kg ha^{-1}. The GFDL-CM4 model also shows a decline from 1991 kg ha^{-1} to 599 kg ha^{-1}, while the GFDL-ESM4 model decreases from 1753 kg ha^{-1} to 735 kg ha^{-1}.

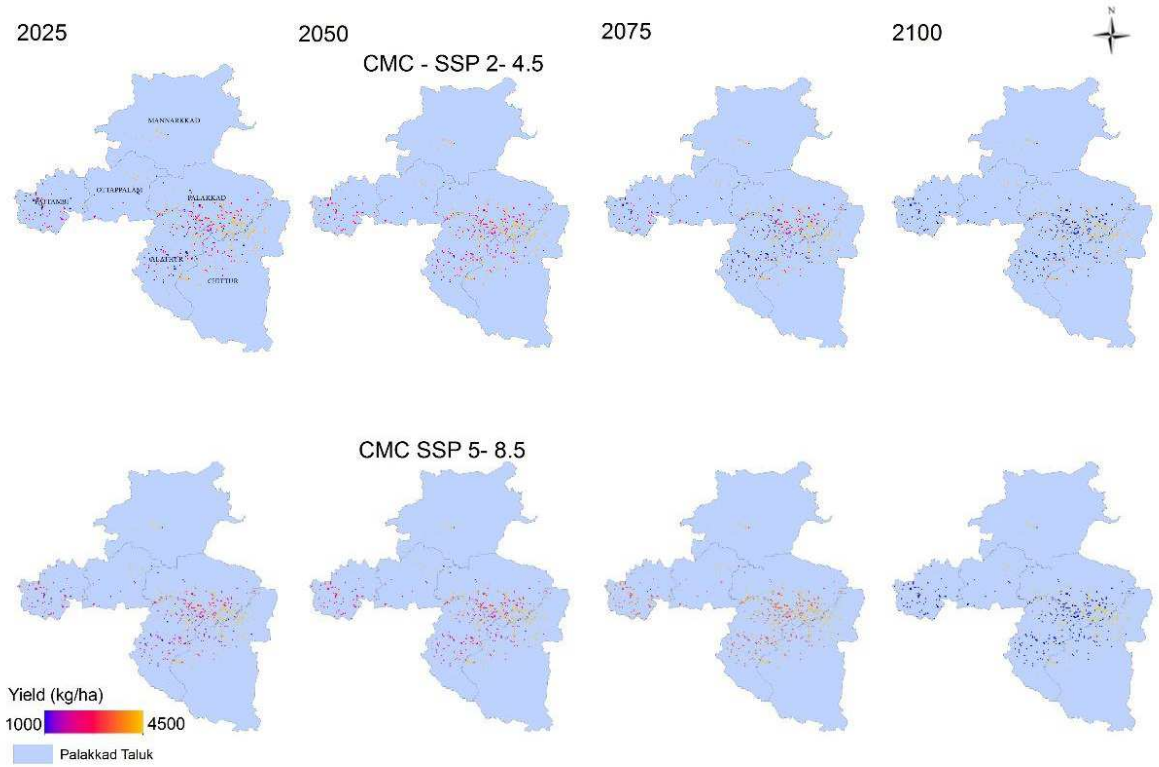


Fig.4.27. Palakkad- Estimated yield for the model CMCC-ESM2

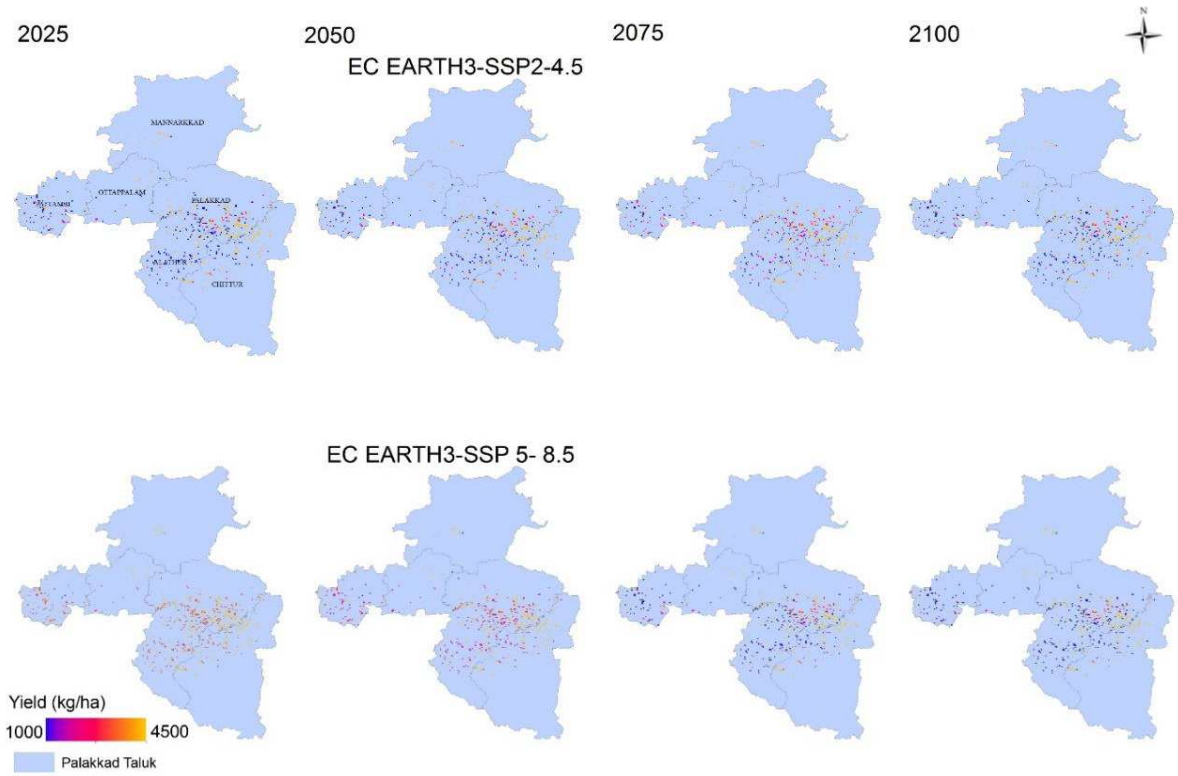


Fig.4.28. Palakkad- Estimated yield for the model EC EARTH

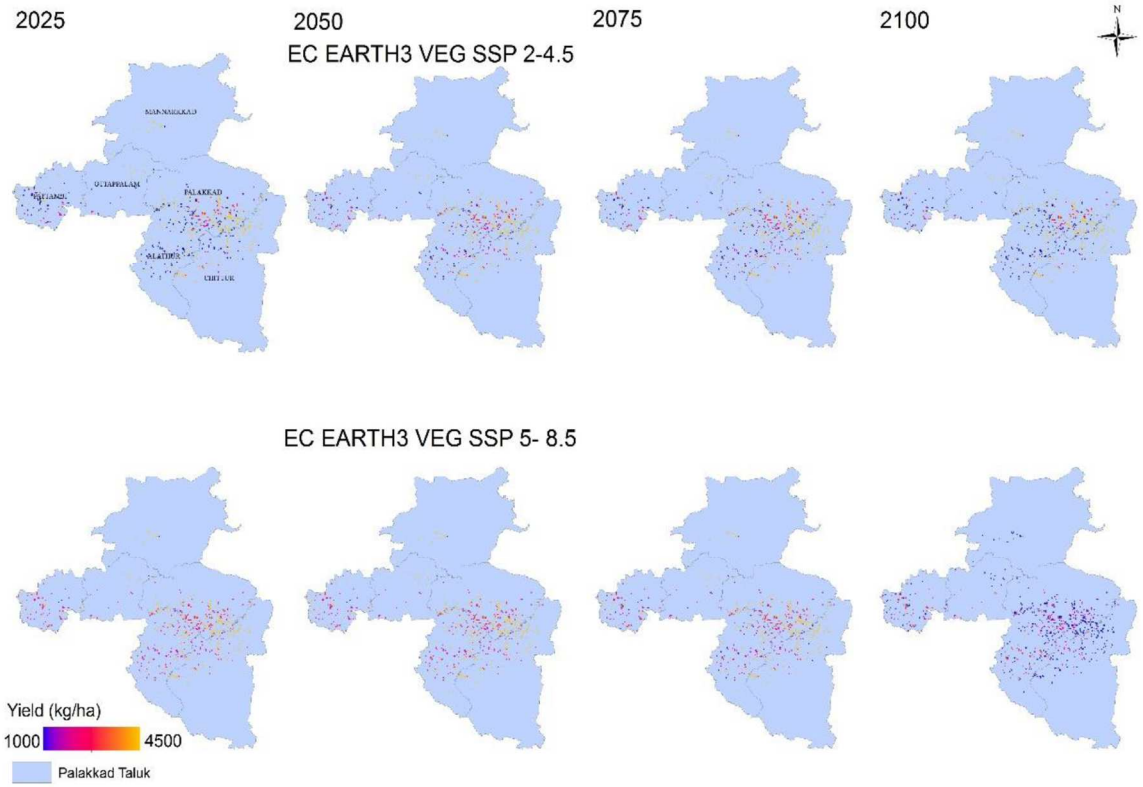


Fig.4.29. Palakkad- Estimated yield for the model EC EARTH- VEG

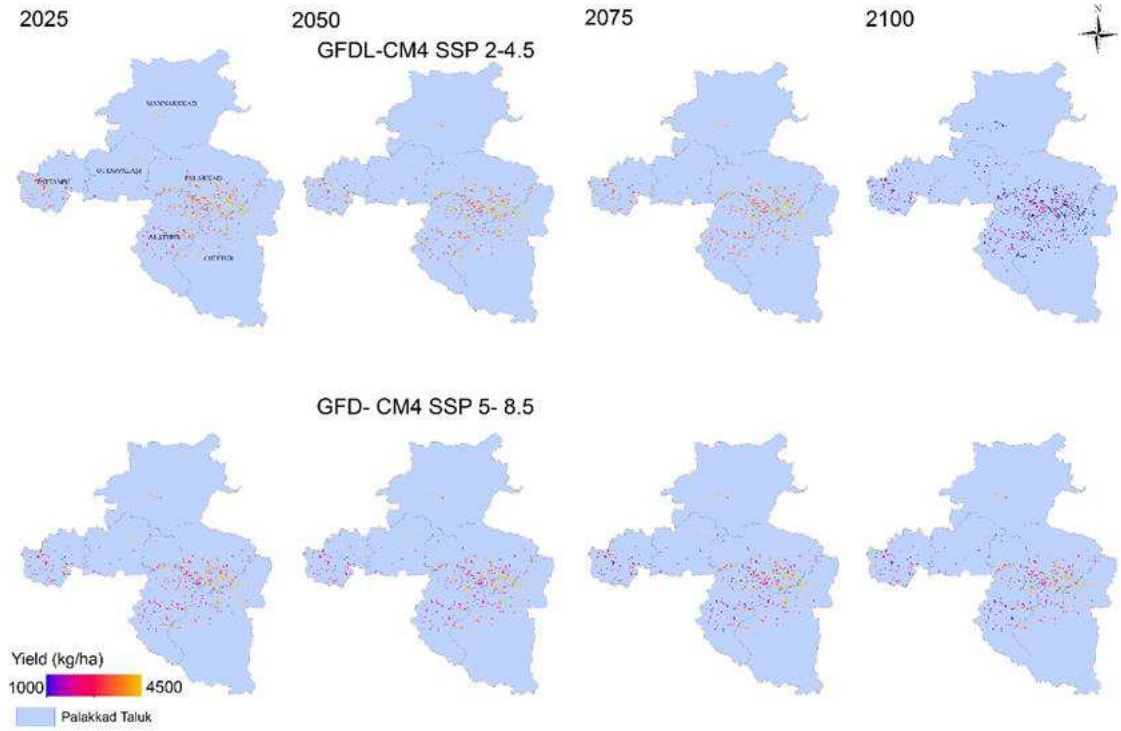


Fig.4.30. Palakkad- Estimated yield for the model GFDL-CM4

4.7.5. Adaption strategies for improving the rice production

By executing scenarios in the DSSAT model, the viability of several adaptation strategies to increase rice yield was also examined. In order to minimize the yield reduction, these adaptation techniques that are being investigated include altering the sowing date, altering the spacing, and planting alternative plant populations as the sowing time approaches. Changing the planting window affected the yield significantly. By planting five days earlier than the actual transplanting date and increasing the N level, the negative effects of the temperature increase on rice yield were lessened.

Preponing the sowing date

The simulated yield by preponing the planting by five days had increased the yields from 4825 kg ha^{-1} to 5468 kg ha^{-1}, i.e., 13.33 %, in P1T1 treatment compared with its simulated yield with the actual planting date. In the P1T2 treatment, change in yield by changing the planting date was 16.06 %, i.e., from 4334 kg ha^{-1} to 5030 kg ha^{-1} (Table 4.37). Yield prediction for P2T1 and P2T2 treatments also had an increment of production by 6.62 % and 8.52 %, respectively. The yield rises from 0.53 % to 11.69 % among all four treatments under 0.5 ^{0} C increase in both maximum and minimum temperature, by preponing the planting date by five, according to a comparison with simulated results obtained via sensitivity analysis prediction. Under a 1.0 ^{0} C increase in both maximum and minimum temperature scenarios, the yield hike ranged from 3.26 % to 13.62 % and for a 1.5 ^{0} C increase in both maximum and minimum temperature scenarios yield increase was 25.92 % to 53.09 % in all four treatments, namely, P1T1, P1T2, P2T1, and P2T2, while comparing with simulated results obtained via sensitivity analysis prediction. Thus, it can be said that increasing rice output in the experimental area benefits from five days of early sowing. In the temperature-sensitive scenarios, it is predicted that five days of early sowing will increase the yield for all treatments.

Increasing nitrogen content in fertilizers

The simulated yield by increasing the nitrogen content by 150 % had increased the yields from 4825 kg ha^{-1} to 5394 kg ha^{-1}, i.e., 11.81 %, in P1T1 treatment compared with its simulated yield with the 125 % inorganic fertilizer application. In the P1T2 treatment, change in yield by changing the planting date was 11.35 %. Yield prediction for P2T1 and P2T2 treatments also had an increment of production by 8.36 % and 9.32 %, respectively (Table 4.38). The yield rises from 5.18 % to 13.61 % among all four treatments under 0.5

^{0} C increase in both maximum and minimum temperature, by increasing the nitrogen per cent in the fertilizer by 150 %, according to a comparison with simulated results obtained via sensitivity analysis prediction. Under a 1.0 ^{0} C increase in both maximum and minimum temperature scenarios, the yield hike ranged from 6.89 % to 12.71 % and for a 1.5 ^{0} C increase in both maximum and minimum temperature scenarios yield increase was 30.39 % to 51.98 % in all four treatments, namely, P1T1, P1T2, P2T1, and P2T2, while comparing with simulated results obtained via sensitivity analysis prediction. Thus, it can be said that increasing rice output in the experimental area benefits from increasing the nitrogen content in the fertilizer.

Table 4.37. Yield prediction before and after changing the planting date

Scenario	2019 simulated (kg ha^{-1})		0.5 ^{0}C increase in Tmax & Tmin (kg ha^{-1})		1.0 ^{0}C increase in Tmax & Tmin (kg ha^{-1})		1.5 ^{0}C increase in Tmax & Tmin (kg ha^{-1})	
Planting date	*on 05/07/2019*	*on 01/07/2019*	*on 05/07/2019*	*on 01/07/2019*	*on 05/07/2019*	*on 01/07/2019*	*on 05/07/2019*	*on 01/07/2019*
P1T1	4825	5468	5101	5426	4904	5064	4039	5086
P1T2	4334	5030	4567	5101	4406	4963	3526	4992
P2T1	3972	4235	3973	3994	3965	4289	3083	4000
P2T2	3638	3948	3658	3743	3604	4095	2505	3835

Table 4.38. Yield prediction before and after changing the nitrogen fertilizer application

Fertilizer application	*125 % N*	*150 % N*	*125 % N*	*150 % N*	*125 % N*	*150 % N*	*125 % N*	*150 % N*
P1T1	4825	5395	5101	5795	4904	5242	4039	5360
P1T2	4334	4826	4567	5101	4406	4903	3526	5162
P2T1	3972	4304	3973	4179	3965	4277	3083	4020
P2T2	3638	3977	3658	3964	3604	4062	2505	3807

Where, P1- DSR, P2- Transplanted, T1 is 125 % of inorganic fertilizers, and T2 is 100 % of inorganic fertilizers.

Discussion

5. Discussion

A study was undertaken to establish rice water and nutrient recommendations using various field experiments, calibration and validation of crop modelling using simulation studies, as well as to quantify the impact of various environmental variables on rice growth and production under changing climate scenarios. In this chapter, an attempt has been made to address the cause-and-effect relationship between the significant observations and results obtained during trials. The topic focuses on how different treatment combinations affect different growth indicators and yields in changing climate situations, as well as how to optimize rice productivity under changing climate scenarios.

5.1. *Experiment -1*

Assessing the influence of nutrient management and method of irrigation on biometric characters of four different rice cultivars

The first experiment was designed to evaluate the effect of different nutrient management and methods of irrigation on four different rice varieties, commonly cultivated in Kerala, on rice growth parameters and discussed the water requirement in each irrigation method.

5.1.1. Biometric characteristics

Plant height

Plant height is one of the important crop biometric characteristics for determining the influence of treatments on plant growth status. In most of the research studies, it may also be used as a sign of a plant's ability to perform under varied conditions of management such as a change in irrigation or nutrient management practices and plant height reflects changes in plants over the crop growth period (Fernandez et al., 2009; Boomsma et al., 2010; Muangprakhon & Kaewplang, 2021). In the first experiment field, plant height was significantly influenced by the applied treatments in general and details are discussed below (Fig.5.1).

Rice plants showed significantly higher plant height under flooded fields than those of the plants under AWD fields, irrespective of all the varieties tested. With respect to stages of the plant, *Uma*, variety showed a significant difference on plant height in all three stages for irrigation treatment, in *Jaya* and *Kanchana* paddy varieties had significant

differences in the panicle initiation stage and the maturity stage, whereas the *Jyothi* cultivar showed substantial impact only in the panicle initiation stage. AWD plants and

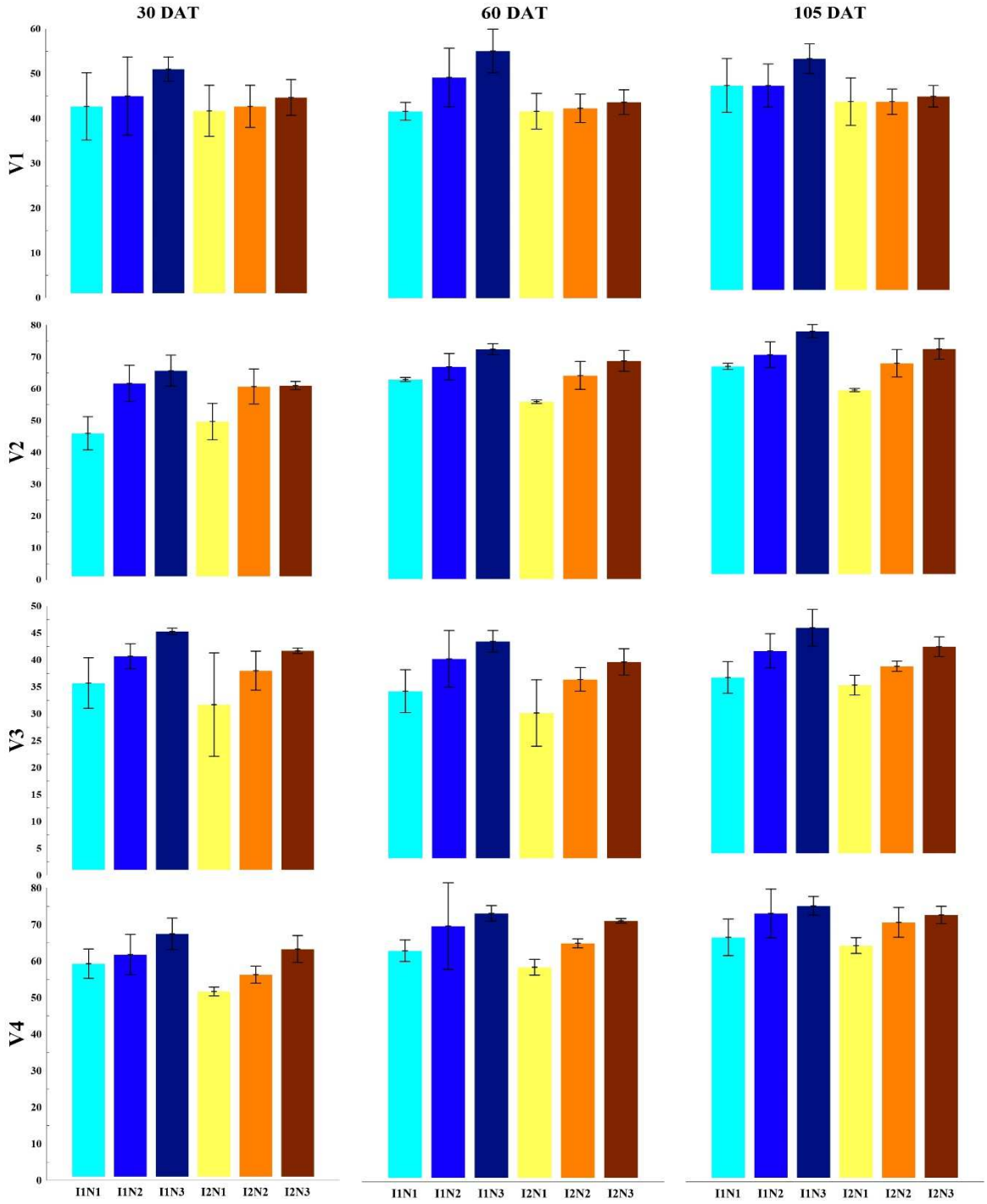


Fig.5.1. Plant height of four different rice varieties at different stages (30, 60, & 105 DAT) are represented as Mean ± Standard Deviation (SD) of three replications. Where, V1 is *Jyothi, V2- Jaya, V3- Uma, V4- Kanchana*. Where, I1 is waterlogged/ flooded, I2 is alternate wetting and drying (AWD), N1 is 0 % application of the recommended dose of nutrients, N2 is 100 % N recommended dose of application of the recommended dose of nutrients through inorganic fertilizers and N3 is 120 % N of the recommended dose of nutrients through inorganic fertilizers.

conventional flooded rice showed observable variations in plant morphology (Thakur et al., 2011). Accelerated internodal elongation, aerenchyma development, cell elongation, food availability, and genetic variables are all adaptations of rice plants to flooding environments. Internodal elongation widens the gaps between nodes, allowing plants to attain maximum height. Plant morphology may be influenced by genetic changes as well. Numerous studies, including Choudhary (2003), Parihar (2004) and Parihar (2004), have observed a significant increase in plant height as a result of flooded irrigation which is in agreement with the current study. In addition, flooded rice fields can suppress weed growth more effectively due to reduced access to light and oxygen for weed germination and growth (Kaspary et al., 2020). This helps in higher growth of the plants by reducing competition for nutrients and space.

Plant height was also significantly influenced and increased by nitrogen (N) application at active tillering stage, panicle initiation period, and maturity stages. During the three developmental stages of rice observed in this experiment, increased percentages of N applications had a significant impact on plant height in the *Uma* and *Jaya* cultivars. Whereas in *Kanchana*, except tillering, both panicle initiation and maturity stage, paddy height was significantly impacted by the N application. Plant height showed a positive response when nitrogen was applied in three splits (Pillai & De, 1980; Yang et al., 2011; Khan, et al., 2022). Also, a sufficient supply of nitrogen supports vegetative growth, including stem and leaf development. In addition to this, increased levels of N contributed to the better development of plants, which was reflected in plant height in all stages of crop growth. This might be due to the constant availability of nitrogen and might have resulted in higher uptake of N resulting in higher plant growth. This is consistent with Glass's (2003) findings. The ability of rice plants to acquire and absorb nutrients from the soil is influenced by their height. Taller plants typically have a larger root system that can explore a wider amount of soil and take more nutrients. Nutrient intake is critical for healthy development and yield. Nitrogen is a fundamental component of chlorophyll and amino acids, both of which are required by plants for photosynthesis and protein synthesis (Ohyama, 2010; Leghari et al., 2016; Asadi et al., 2023). The interaction impacts of water management and N levels were not significant for plant height under this experimental site, which is consistent with the findings of Zhang et al., (2011).

Number of tillers

Tillering is one of the critical growth stages in rice plants that has a direct impact on yield potential (Bakhsh et al., 2011). The amount of N application and irrigation management have an impact on tiller formation at the peak tillering and panicle initiation stages of the paddy crop. Treatments significantly influenced the number of tillers and with respect to water management, flooding resulted in a higher number of tillers in all three varieties except *Kanchana* (Fig.5.2). A sufficient quantity of water is essential for tiller development and paddy prefers submerged condition for producing more number of tillers. This is in confirmation with many of the earlier studies, which also reported during the tillering stage, that flooded fields favour more tillering. (Juraimi et al., 2009; Zhu et al., 2018). Rice plants respond to flooding by lengthening their internodes to reach the water's surface. Tillering is encouraged as a result, since submerged nodes are stimulated to grow new shoots (Mon, 2018). Tillering more often results in more productive tillers, which in turn influences the rice crop's potential production. It has been observed that in certain situations, AWD could result in fewer tillers than when conditions are consistently saturated (Thakur et al., 2011; Sudhir-Yadav et al., 2011; Howell et al., 2015; Norton et al., 2017). The sporadic drying interval under AWD may have an impact on the initiation and survival of tiller buds, which could explain the decrease in tillering.

Among the nutrient management treatments T3 produced more tillers in the case of all four varieties and it was statistically significant, since nitrogen is an important ingredient for paddy plant tillering. Tiller production can be stimulated by using 120 % N fertilizers at the appropriate growth stages (Alley et al., 2009; Wu et al., 2020). This is in agreement with the current results. Tiller production was often increased by applying nitrogen in split doses at the tillering and panicle initiation stages (Pillai & De,1980; Kamruzzaman et al., 2014). This is consistent with Tanaka and Garcia (1965) and Sui, et al., (2013) findings, which showed that mineral nutrition could significantly alter the tillering performance of rice and that the rate of N uptake between the panicle initiation and flowering stages is more crucial for influencing tiller production than the amount absorbed or stored in the plant. Finally, the interaction effects of water management, and N rate were not significant in all varieties except *Uma* cultivar, where, panicle initiation and maturity stages had a significant interaction effect on the number of tillers. This is due to the combined influence of proper irrigation and, N availability, during the growth period which might have improved water and nutrient uptake and growth of the crop (Mandal et al. 2013; Reddy et al., 2013). So, together with the innate genetic traits, these factors aided the *Uma* cultivar in becoming more receptive to local management and the environment.

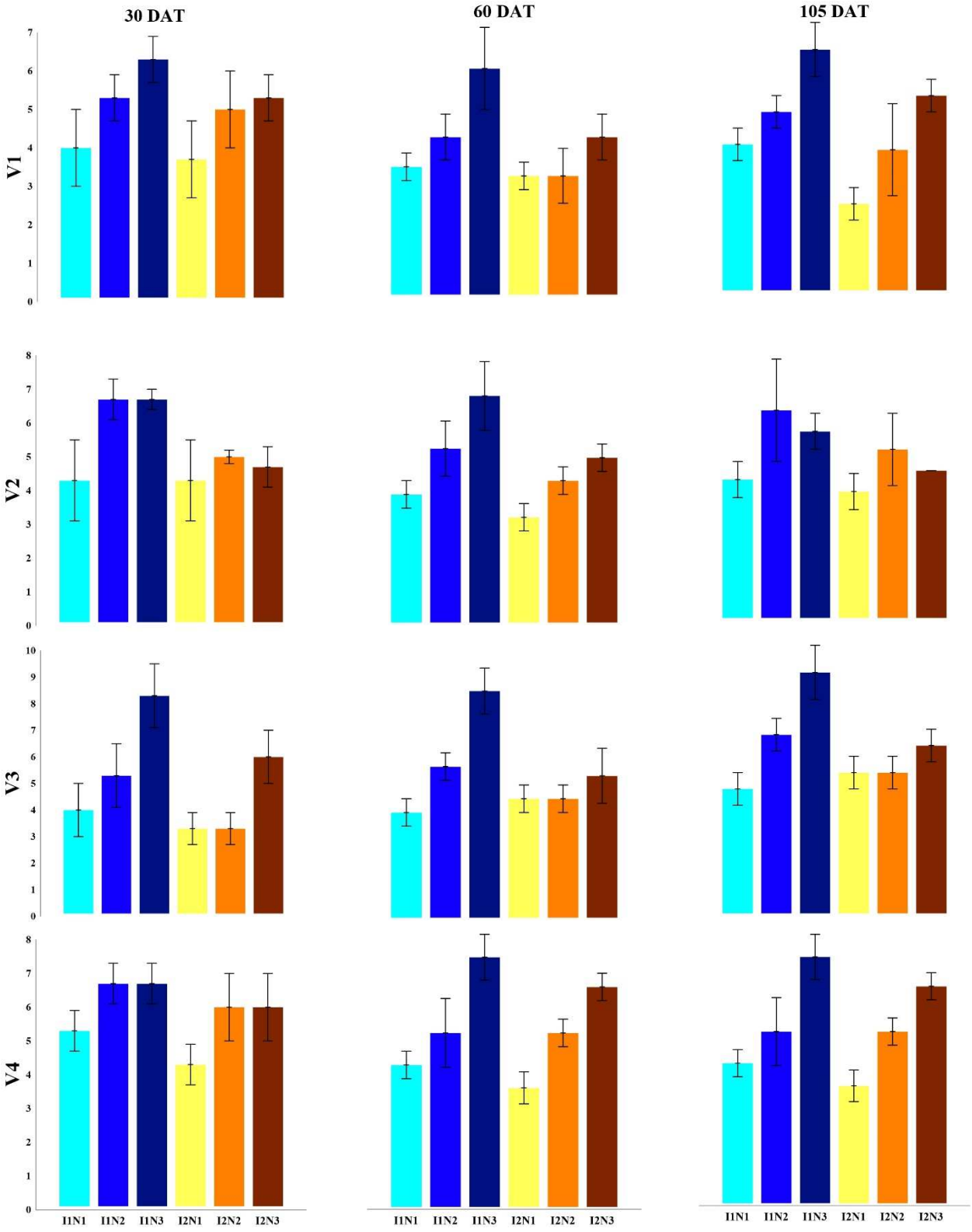


Fig.5.2. Number of tillers of four different rice varieties at different stages (30, 60, & 105 DAT), are represented as Mean ± Standard Deviation (SD) of three replications. Where, V1 is *Jyothi, V2- Jaya, V3- Uma, V4- Kanchana*. Where, I1 is flooded, I2 is AWD, N1 is 0 % application of recommended dose, N2 is 100 % N through inorganic fertilizers and N3 is 120 % of the recommended dose of N nutrients through inorganic fertilizers.

Leaf area index (LAI)

The Leaf Area Index (LAI) is an important parameter that calculates the total leaf area of plants per unit of ground surface area. Also, is an important indicator in rice production since it gives important information about the crop's growth, photosynthetic capability, nutritional requirements, and overall health at various stages of development and this is the important factor used in crop simulation modelling for prediction of crop yield. LAI values increased from the initial tillering stage to the panicle initiation stage, and then it began to decline at the maturity stage (Wopereis et al., 1996; Zhang et al., 2019; Fukuda et al., 2021). The results of LAI are graphically represented in Fig.5.3.

With the exception of the *Kanchana* variety, the remaining ones showed notable effects from fertilizer treatments as well as irrigation. Flood irrigation and 120 % of the recommended dose of N nutrients from inorganic fertilizers produce more LAI in rice crops and this will contribute to the higher yield. Plants under flooded conditions produced more tillers and leaves, which will raise their LAI. The constant presence of water guarantees an environment that is beneficial to the growth of leaf area (Clerget et al., 2016). Therefore, compared to continuous flooding, periods of dryness in AWD may temporarily slow down plant growth and result in a slightly lower LAI. According to Sharma & Yadav (1999) and Ciampitti & Vyn (2011), during the reproductive period, LAI increased with increased N rate, which is in agreement with the present results. As a result of its impact on photosynthetic levels, the high leaf area index (LAI) at flowering is closely associated to grain yield (Fagade & De Dutta, 1971; Qi, et al., 2020). Monitoring LAI during the growth season assists farmers and researchers in understanding how the canopy changes over time and how this is influencing the yield may be understood. This data is essential for optimizing agronomic activities like fertilizer application and irrigation scheduling. LAI monitoring and management can result in higher rice yields and more sustainable agricultural techniques. Under tropical conditions, the combined effects of water management, and N application were not significant and this is in agreement with the study conducted by Zhang et al., (2012).

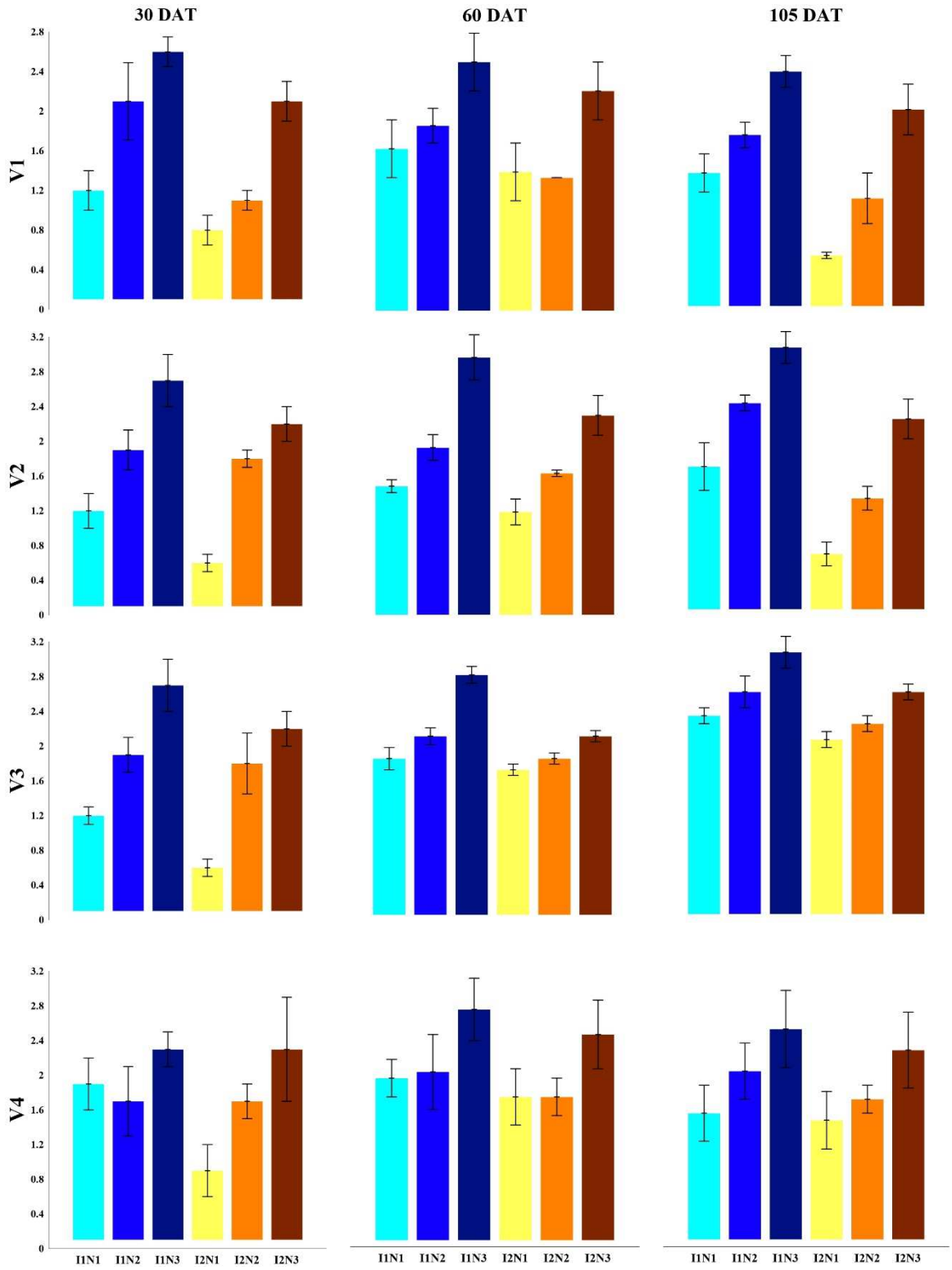


Fig.5.3. LAI of four different rice varieties at different stages (30, 60, & 105 DAT), are represented as Mean ± Standard Deviation (SD) of three replications. Where, V1 is *Jyothi, V2- Jaya, V3- Uma, V4- Kanchana*. Where, I1 is waterlogged/ flooded, I2 is alternate wetting and drying (AWD), N1 is 0 % application of the recommended dose of nutrients, N2 is 100 % N recommended dose of application of the recommended dose of nutrients through inorganic fertilizers and N3 is 120 % N of the recommended dose of nutrients through inorganic fertilizers.

Number of panicles

The number of panicles in rice is an important aspect that can affect yield and grain quality. In the present study, the nitrogen application treatment had significant influence on number of panicles produced by all four varieties (Fig.5.4). Treatment combinations of waterlogged environment/ flooded water management and 120 % application of the recommended dose of nutrients through inorganic fertilizers treatment at the panicle initiation stage resulted in the highest number of panicles in all the four rice varieties. The *Uma* rice variety had a significant combined effect on the number of panicles for both water and nutrient management. This is because adequate irrigation and nitrogen availability during the growing season enhanced the crop's ability to absorb nutrients and grow (Mandal et al., 2013; Reddy et al., 2013). Water and fertilizer supply, as well as climate and growing circumstances, all have an impact on panicle formation Thus, in addition to the inherent genetic characteristics, these elements helped the Uma cultivar become more sensitive to environmental influences and local management.

Also, for every rice growth variable, N1 treatment with 0 % nitrogen application had the least or inferior values. Insufficient nitrogen or no nitrogen application can cause rice plants to develop slowly, and produce less grain by reducing tillering, yellowing of the leaves (chlorosis), and stunting of growth with results in poor growth and yield characters (Shrestha et al., 2020; Gunawan, et al., 2023). AWD with 100 % N and120 % N produce numerically improved growth characters. However, the observed reduction in the number of panicles in the AWD experiment is contradictory with the studies of Yao et al. (2012), Liu et al. (2013), Norton et al. (2017), Monaco et al. (2021) and Jiang et al. (2023), it might be due to other environmental factors observed with the midland laterites apart from the other environmental settings. The growth of chlorophyll, which is necessary for photosynthesis, depends on nitrogen. It is also an essential part of proteins, nucleic acids, and amino acids. Hence, proper nitrogen and irrigation treatment management is critical for increasing the number of panicles and increasing rice production. The ability to balance these elements based on the local environmental conditions is critical for achieving good yields and quality in rice farming (Fahad et al., 2019). Other than this, several other factors determine the number of panicles in rice plants, including growth behaviours, genetic features, and management approaches (Mzengeza, 2010; Mohapatra, 2013). Panicle number is influenced by genetic variation within each subspecies (Singh et al., 2022b).

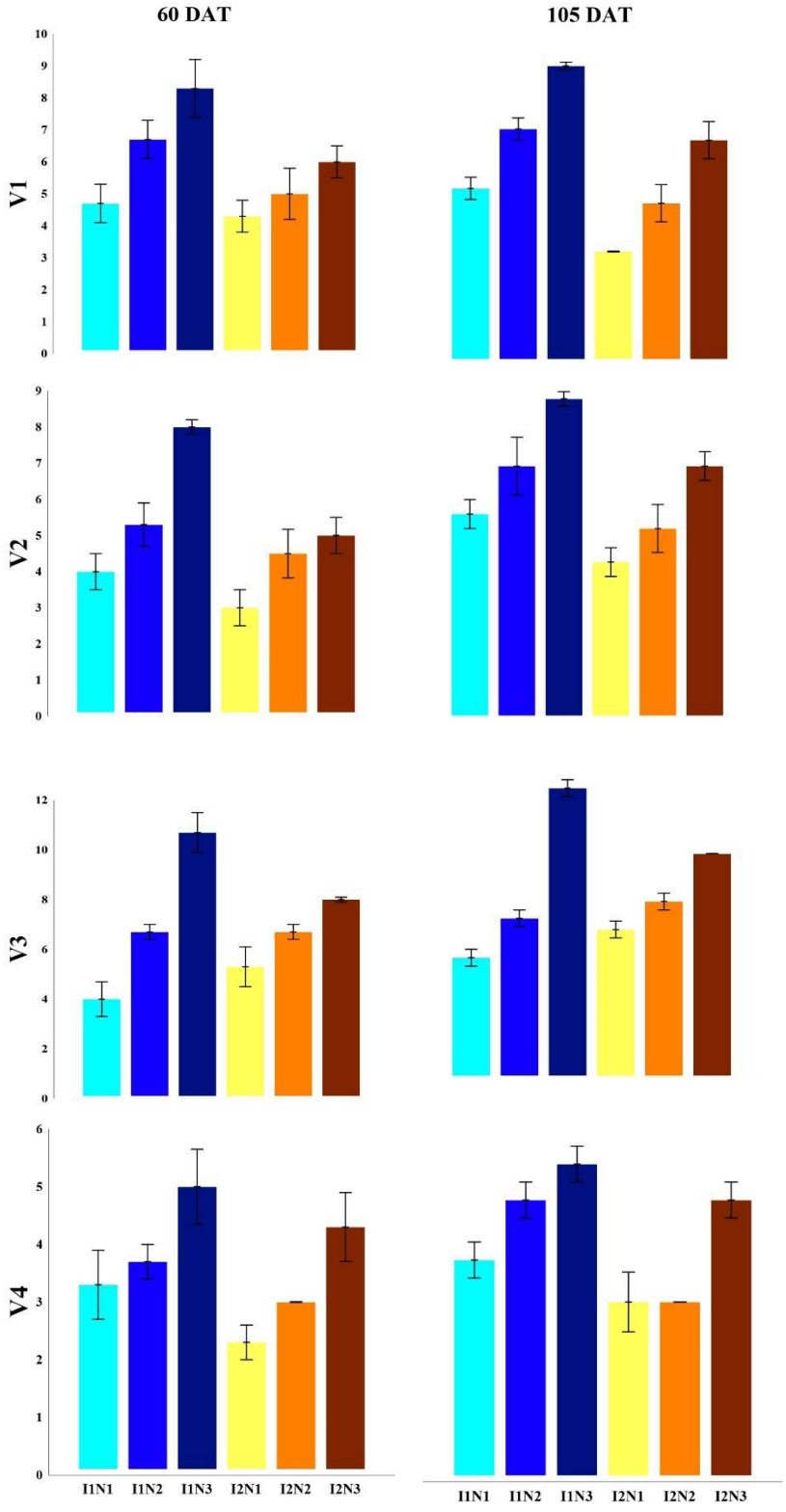


Fig.5.4. Number of panicles of four different rice varieties at different stages (60, & 105 DAT), are represented as Mean ± Standard Deviation (SD) of three replications. Where, V1 is *Jyothi, V2- Jaya, V3- Uma, V4- Kanchana*. Where, I1 is waterlogged/ flooded, I2 is alternate wetting and drying (AWD), N1 is 0 % application of the recommended dose of nutrients, N2 is 100 % N recommended dose of application of the recommended dose of nutrients through inorganic fertilizers and N3 is 120 % N of the recommended dose of nutrients through inorganic fertilizers.

5.1.2. Water saving

The AWD irrigation system asserts that it can conserve up to 20–50 % of water without compromising rice growth, depending on the climate, soil type, degree of dryness, crop duration, and crop growth stage. (Massey et al., 2014; Carrijo et al., 2017; Chandana et al., 2019; Widodo & Muhklisin, 2022). 37.52 % of water input was saved in this experiment (Fig.5.5). In addition to the water savings, AWD can reduce greenhouse gas emissions (Cheng et al., 2022; Haque et al., 2021; Ishfaq, et al., 2020; Win et al., 2020; Linquist et al., 2014; Wassmann et al., 2010). Therefore, incorporating water-saving technologies like AWD/ aerobic rice cultivation in suitable locations can be addressed as sustainable rice farming practices.

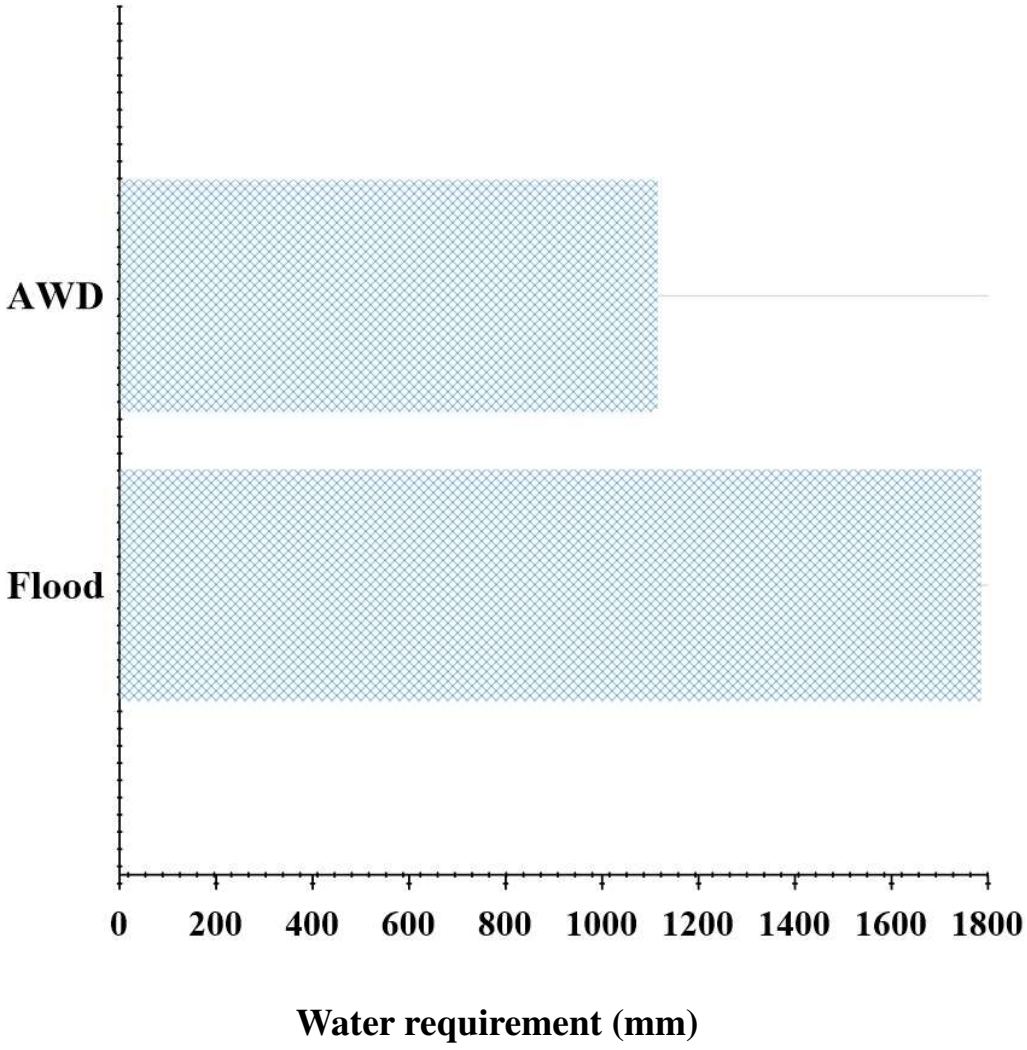


Fig.5.5. Water requirement (mm) for Flood and AWD irrigation systems during the experiment.

Addressing water scarcity in agricultural practices, particularly in flooded rice systems, necessitates a concerted effort towards implementing alternative methods for sustainable water management. As the demand for food rises and climate change exacerbates water shortages, embracing innovative approaches becomes imperative. Sustainable agriculture, marked by responsible water use, not only safeguards ecosystems but also ensures food security for a growing global population. Embracing these alternative methods like AWD, aerobic cultivation, SRI (System of Rice Intensification) (Surendran et al., 2021), not only offers a lifeline to regions grappling with water scarcity but also heralds a promising era of resilient and environmentally conscious agriculture.

5.2. *Experiment -2*

Assessing the savings in Water with FAO-CROPWAT model and evaluating different strategies on crop productivity of aerobic rice (Sruthi and Surendran 2023)

From the previous study, the importance of water-saving technologies was identified hence next experiment was conducted under aerobic conditions. Thus, the purpose of the second experiment was to evaluate the aerobic rice management techniques. This experiment was carried out to assess various nutrient management strategies and planting techniques for aerobic rice production. Additionally, an effort was made to measure the amount of water saved by aerobic rice. The results obtained from this experiment are discussed hereunder.

5.2.1. Biometric characteristics

Plant height

One of the important morphological characteristics linked to grain productivity is plant height (Fageria, 2007). It is a reflection of how the crop's growth has been affected by natural and management conditions. Results showed that biometric characteristics of the plants were significantly influenced by the different nutrient management practices and methods of planting. Among the different nutrient management practices during all the stages of observation, namely, 30th day, 50th day, 85th day, and 115th day, significantly taller plants were observed under 125 % inorganic nutrient management (T1) practice, followed by 100 % integrated nutrient management practice (T2), and then organic nutrient management (T3) in decreasing order of growth parameters, and treatments differing significantly from each other (Fig.5.6). The application of higher dose of inorganic

fertilizer has a good effect on plant height. NPK, in particular nitrogen, plays a role in cell proliferation, elongation, internode lengthening and growth consequently at the base of rice stems, which may have contributed to an increase in plant height. (Zaman et al., 2015; Shah et al., 2017; Zhang et al., 2021; Liu et al., 2022; Mboyerwa et al., 2022). Organic nutrients, such as manure and compost, even though it may have the all the nutritional composition that plants need, however its availability and quantum of nutrients may be insufficient. The lower concentrations of macronutrients in such organic manures (nutrients essential for the optimal growth of plants) may cause slower or stunted growth. Additionally, the slow release and breakdown of organic components, requires these plant essential nutrients, which might have hindered the development pace of the plants. Conversely, synthetic fertilizers may release nutrients more quickly, resulting in higher plant growth.

In the case of the method of planting, direct seeded rice performed better and produced a significant difference in plant height than the transplanting method. Significant reduction of plant height under the transplanting method as compared to DSR, is contradictory to many of the earlier studies (Hou et al., 2019; Lee et al., 2021), which showed that transplanting results in higher yield attributes because of low competition for resources due to less plant population in the transplanted method and high weed growth in DSR methods (Surendran et al., 2021). In this study, the higher plant height observed in DSR might be due to the line sowing technique, maintaining the plant population as well as timely weed management operations carried out during the experiment. Also, a significant combined interaction effect on methods of planting and different levels of nutrients was found in rice crop, during all four observed stages in this experiment.

Number of tillers

Rice planting practices and fertilizer regimes have a significant impact on the effect of tiller production (Dingkuhn et al., 1990; Badshah et al., 2014). On the 30th, 50th, 85th, and 115th day of observation, among the various nutrient and planting management practices, noticeably higher number of tillers were found under 125 % inorganic nutrient management (T1) practice, while lower number of tillers were found under the T3 treatment (Fig.5.6). The number of tillers of plant is positively impacted by the use of inorganic fertilizer. NPK is important for cell division and proliferation near the base of rice stems. These processes may have led to an increase in number

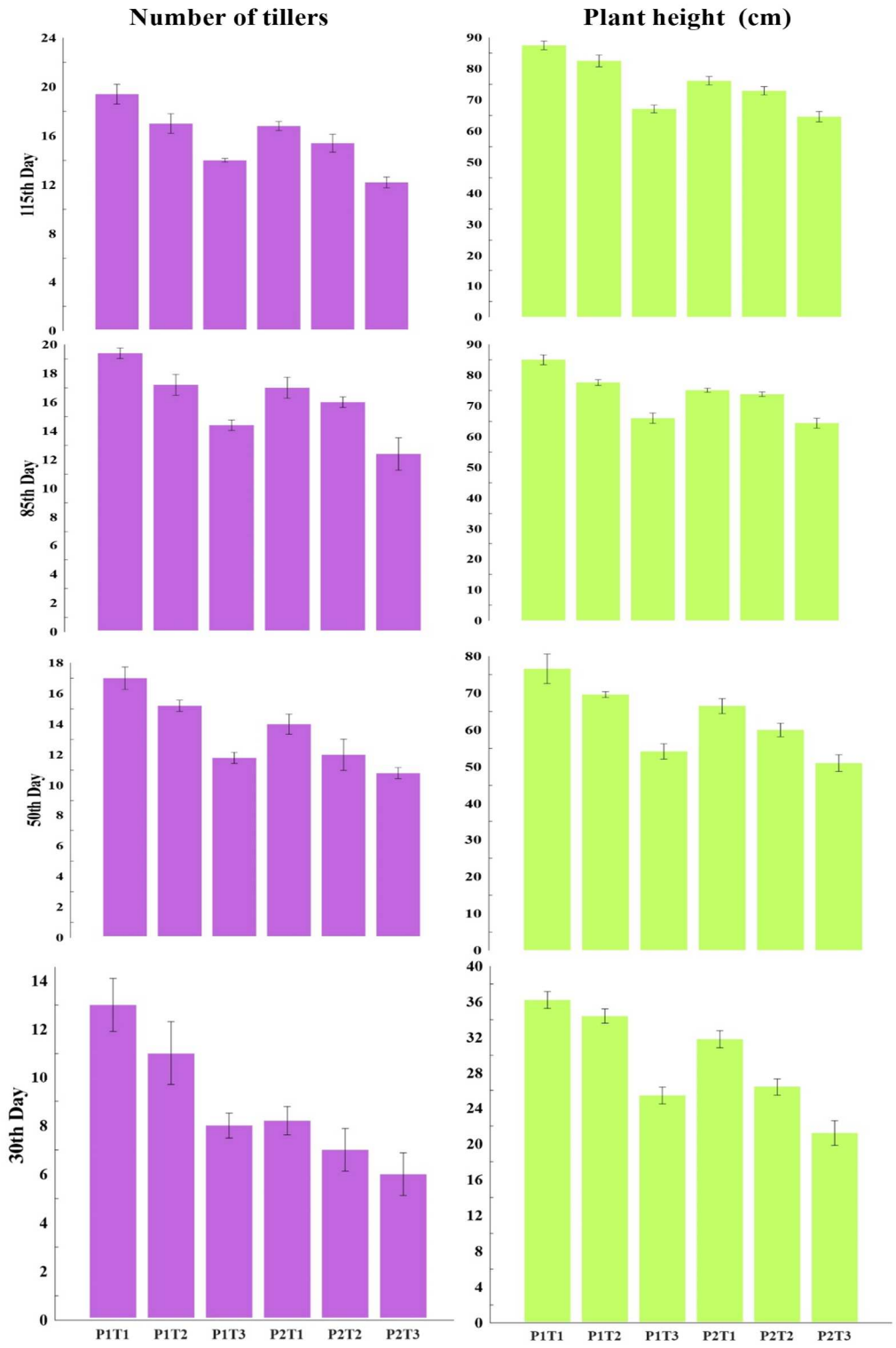


Fig.5.6. Growth characteristics such as number of tillers and height of the of rice plant *cv. Uma*, are represented by its mean value of six replications. Error bar represented as the standard error (SE) of the six replications.
Where, T1- 125 % of inorganic fertilizers, T2 – 100 % of inorganic fertilizers and T3- 100 % of organic manures, P1 -DSR, P2- transplanted

of tillers (Zhang et al., 2021; Liu et al., 2022; Mboyerwa et al., 2022; Zaman et al., 2015; Shah et al., 2017).

Under the transplanting approach, the number of rice tillers exhibited a considerable decrease whereas in DSR significant increase was recorded. In contrast to rice that has been transplanted, direct-sown plants often face greater competition from weeds for resources including light, nutrients, and space, which leads to fewer productive tillers per plant (Nagargade et al., 2018). However, line sowing, seed density, planting depth, and appropriate weed management can all have a good impact on the development of tillers in direct-sown rice. Rice plants may be more able to access nutrients if inorganic fertilizer is applied in excess of the recommended dose (i.e., beyond 100 %) and can encourage tillering and vegetative development in rice. A significant combined interaction effect on the method of planting and different levels of nutrients on the number of tillers was found in this experiment, during all four observed stages.

5.2.2. Yield

The findings from this experiment indicated a significant impact of planting methods and nutrient management practices on paddy yield. Specifically, Direct Seeding of Rice (DSR) outperformed the transplanted method, and in terms of nutrient management, applying 125 % of the recommended dose of inorganic N fertilizers led to a higher yield compared to organic manure application (Fig. 5.7). The increased nutrient quantity significantly influenced plant growth and other yield characteristics, attributed to enhanced nutrient availability and favourable soil characteristics. This, in turn, positively influenced the plant growth and, resulting in higher growth and yield parameters, as observed by Sruthi and Surendran in 2023 (Full paper can be accessed on the following link- https://doi.org/10.1007/s10333-023-00941-x). In addition, dry matter translocation from stems and leaves into grains exhibited a significant increase with rising N application, as indicated by Zhang et al. (2009). In contrast, poor yield was observed with the application of organic manure, possibly due to a lower availability of readily accessible soil nutrients for uptake. However, literature reviews suggest that while organic farming may initially yield lower productivity compared to intensive chemical fertilizer application, its long-term practice enhances soil quality, leading to increased productivity over time (Hiltbrunner, 2004; Kulak, 2014). To support farmers during this transitional period, additional subsidies are recommended to promote the adoption of organic farming approaches.

In contrast to the numerous earlier studies suggesting higher yield attributes with transplanting than Direct Seeding of Rice (DSR) due to lower plant population and increased weed growth (Ali et al., 2014; Surendran et al., 2021; Sruthi and Surendran 2023), this experiment results demonstrate that DSR outperformed transplanting. This might be due to direct seeding of rice as line sowing and not broadcasting resulted in higher plant population. Earlier few studies, including the work of Akhgari & Kaviani (2011), align with our findings, indicating that the DSR planting method yielded the best results in terms of total tillers number, panicle count, and overall yield. Apart from the reasons outlined earlier, this favourable outcome in DSR could be attributed to the transplanting shock experienced by rice seedlings under transplanting in midland soils during early tillering stages, which is sensitive and may lower growth and yield parameters. In contrast, DSR provides a more adaptive timeframe, potentially contributing to its superior performance, since plant population is maintained in this case. Additionally, the use of line sowing techniques in DSR, along with careful plant population management and timely weed control operations, might have contributed to the observed higher yield attributes.

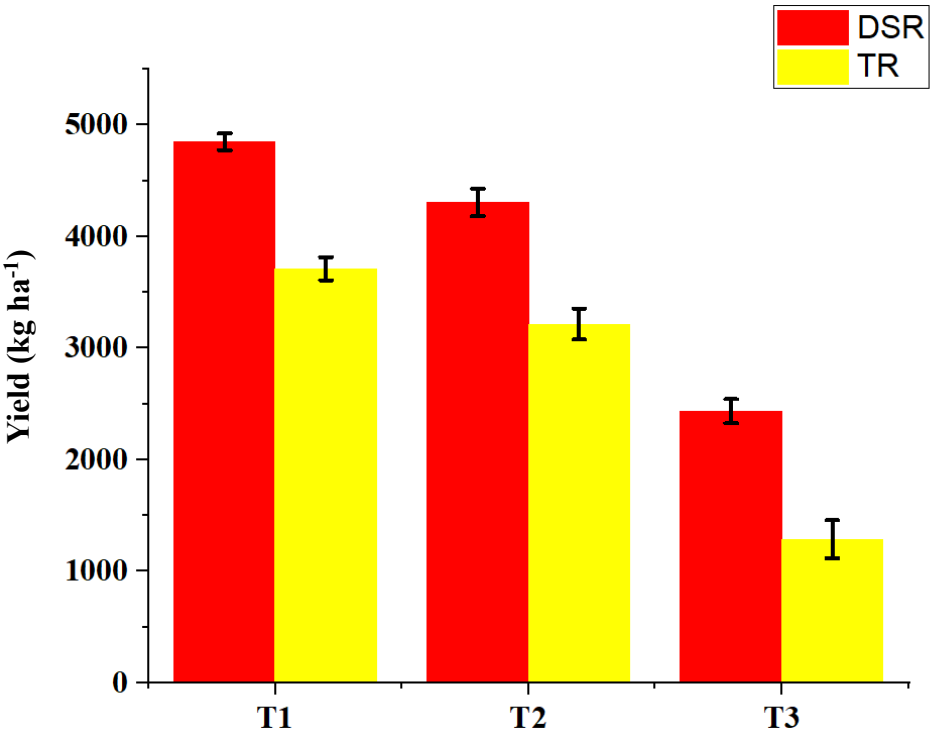


Fig.5.7. Yield of rice *cv. Uma* (kg ha^{-1}) is represented as the mean value of six replications. Error bar represented as the standard error.
Where, DSR is directly sworn rice, TR is transplanted rice, T1 is 125 % of inorganic fertilizers, T2 is 100 % of inorganic fertilizers and T3 is 100 % of organic manures.

The lower yield observed in the transplanting method may be attributed to the setback experienced by plants when transferred from the nursery, whereas in Direct Seeding of Rice (DSR), plants might have adapted to the conditions from the outset (Ali et al., 2014; Sruthi and Surendran, 2023). During the vegetative growth stage, it is crucial to ensure adequate land submergence from transplanting to prevent damage to establishing seedlings and promote proper root development—a factor that may not have occurred under aerobic rice cultivation. Previous studies have indicated that even under anaerobic rice conditions, moisture stress during the active tillering phase can lead to a yield reduction of approximately 30 % (Bouman et al., 2007).

Farmers Participatory Action Research Program (FPARP) in India, demonstrated higher production in DSR than flooded fields and a 20 % water savings, although this reported yield gain was not consistently observed in many of the experimental plots (Gupta et al., 2003). For instance, one of the studies found that DSR yielded higher (13–18 %) with reduced total water inputs (8–12 %) compared to transplanted rice (Ishfaq et al., 2020). The adoption of line sowing techniques, maintaining optimal plant population through proper gap filling, timely weed management operations, and nutrient availability may contribute to higher yields. While observed yield increases are promising, caution should be exercised before widespread implementation of this technique. Comprehensive investigations into appropriate aerobic rice cultivars, optimal management practices, and factors such as organic farming need to be considered before scaling up the adoption of DSR.

5.2.3. Water saving

All three rice growing seasons—Viruppu, Mundakan, and Puncha—were considered when estimating water savings, and the results revealed that approximately 37 % of water can be conserved. Figure 4.3 illustrates irrigation water savings when converting 20 %, 40 %, 60 %, 80 %, and 100 % of the total rice-cultivated areas in Kozhikode district from flood cultivation to the aerobic method. These simulations yielded water savings ranging from approximately 55 mm to 550 mm for 10 % to 100 % of the total rice-cultivated areas. In other words, transitioning from an anaerobic to an aerobic method of rice cultivation resulted in water savings ranging from 7.15 % to 35.77 %. This aligns with earlier reports indicating water savings of 35 % to 57 % for Direct Seeding of Rice (DSR) in non-puddled soil near field capacity (FC) saturation compared to

continuously flooded (5 cm) transplanted rice (Ladha et al., 2003; Reddy et al., 2020; Chadhar et al., 2020; Sruthi and Surendran 2023).

The adoption of water-saving techniques in rice cultivation not only enhances paddy yield but also contributes to carbon sequestration, resource conservation, and reduction in greenhouse gas (GHG) emissions (Yang et al., 2017) especially methane. The growing scarcity of water resources has resulted in identification and development of new methods such as adoption of aerobic rice systems, which conserve water inputs and enhance water productivity by minimizing water use during land preparation and mitigating seepage, percolation, and evaporation during cultivation.

In this study, a comparison of planting methods and nutrient management under aerobic rice cultivation revealed that Direct Seeding of Rice (DSR) outperformed the transplanted method, and employing 125 % of the recommended dose of inorganic nitrogen fertilizers (RDIF) resulted in higher yields compared to organic manure application. Additionally, water savings amounted to 36.4 %, as compared to the FAO-CROPWAT based anaerobic rice water requirement, consistent with findings from previous studies (Ladha et al., 2003). To conclude, the direct method of line sowing, coupled with 125 % of the recommended dose of inorganic fertilizers, demonstrates the potential for achieving higher crop and water productivity in rice

5.3. *Experiment -3*

Assessing the different levels of water and nutrient application on growth and productivity of rice under aerobic cultivation

This experiment was designed to evaluate the effect of different levels of water and nutrient management practices on aerobic rice yield. The previous study recommended using DSR along with line sowing as a better planting technique for rice cultivation; however, this study chose to use transplanted planting in order to replicate typical agricultural operations used in the farmer's field. During the field experiment, the leaf rolling phenomenon was observed in some patches of the experimental plot. Hence, we conducted a brief study to understand the leaf-rolling issue in paddy and to assess its leaf rolling behaviour under different moisture-absorbing mediums. The results obtained from this experiment are discussed hereunder.

Initial experiment

5.3.1. Biometric characteristics

Plant height

Results of the experiment showed that (Fig.5.8), among the treatments attempted, statistically significant differences were observed. Both water and nutrient management treatments had a significant effect on plant height during the initial and/ or the final stages. The study found that higher nitrogen levels (125 % N) provided optimal conditions for enhanced plant height, suggesting that plants responded positively to higher nitrogen levels. The combination of 125 % N application and suitable irrigation (100 % or 120 % ET_C) created optimal growth conditions for aerobic rice. Understanding these factors is crucial for optimizing crop performance. An optimum amount of water availability is crucial for nutrient uptake and transport within the plant. Adequate water availability ensures that nutrients, including nitrogen, are efficiently transported to the growing points, promoting plant height. (Leghari, et al., 2016). Nitrogen is a vital component of amino acids, proteins, and chlorophyll, essential for plant growth. (Ohyama, 2010). So, a higher nitrogen supply encourages robust shoot development, resulting in increased plant height.

Number of tillers

The results showed that in aerobic rice cultivation, the number of tillers was significantly affected by nutrient and water management treatments (Fig.5.8). Minimum number of tillers was found in the I1N1 treatment and the maximum number of tillers was found in the I2N3 treatment. Aerobic rice cultivation involves varying combinations of nutrient and irrigation management significantly influence the number of tillers. Nutrient management, such as applying 75 % nitrogen, limit out the tiller development. 100 % nitrogen provides optimal nutrient supply, promoting balanced growth. Excess nitrogen (T3 – 125 % N application of inorganic fertilizers) can stimulate vigorous growth, including increased tiller formation (Yang et al., 2019). Adequate irrigation at 100 % Evapotranspiration (ET_C) ensures plants receive sufficient water, favouring the development of an appropriate number of tillers. However, results confirmed that increasing irrigation to 120 % ET_C might not necessarily increase tiller production. The interactions between nutrient and irrigation management are complex and require optimization for optimal crop growth and yield.

Also, the development of axillary buds, which are in charge of tiller development, is greatly aided by nitrogen. Increased nitrogen concentrations may help these buds begin and expand (Liu et al., 2011). Ramesh et al. (2009) study was similar to the current study and stated that increases in nitrogen levels up to 120 to 175 kg N ha^{-1} were linked to the rise in tillers per hill. An abundant supply of nitrogen and water minimizes resource competition amongst plants in the field and ensures that the plant forms an enduring tillering pattern from the initial stage. Each plant is more likely to produce more tillers if it has access to enough water and nutrients.

Photosynthesis rate

The nutrient management treatments had a significant effect on the photosynthetic rate (Fig.5.8). Highest value for photosynthetic rate was found in I2N3 and the lowest was measured in the I2N1 treatment. Similar findings were published by Hassan et al. (2007), who suggested that low nitrogen levels can lower leaf chlorophyll concentration, photosynthetic efficiency, and photosynthetic rate. Increased nutrient concentration, particularly essential nutrients like nitrogen can alleviate nutrient limitations that may have been restricting photosynthesis. Adequate nutrient supply enhances the uptake and assimilation of nutrients by paddy plants, promoting the synthesis of chlorophyll and other photosynthetic pigments. Furthermore, a high concentration of nutrient availability supports various metabolic processes within the plant, ensuring smooth functioning and increased photosynthetic activity (Song et al., 2013). However, the irrigation management failed to affect the photosynthetic rate in this experiment. Possible reasons include the optimal water availability for the plants, their adaptation to aerobic conditions, other limiting factors, experimental conditions, and variability in plant response. The photosynthetic process is complex and may not be fully influenced by these factors (Kaiser et al., 2014; Neto et al., 2021). Optimizing irrigation practices for improved photosynthetic performance may require a more specific approach, considering the specific requirements and adaptations of aerobic rice cultivars.

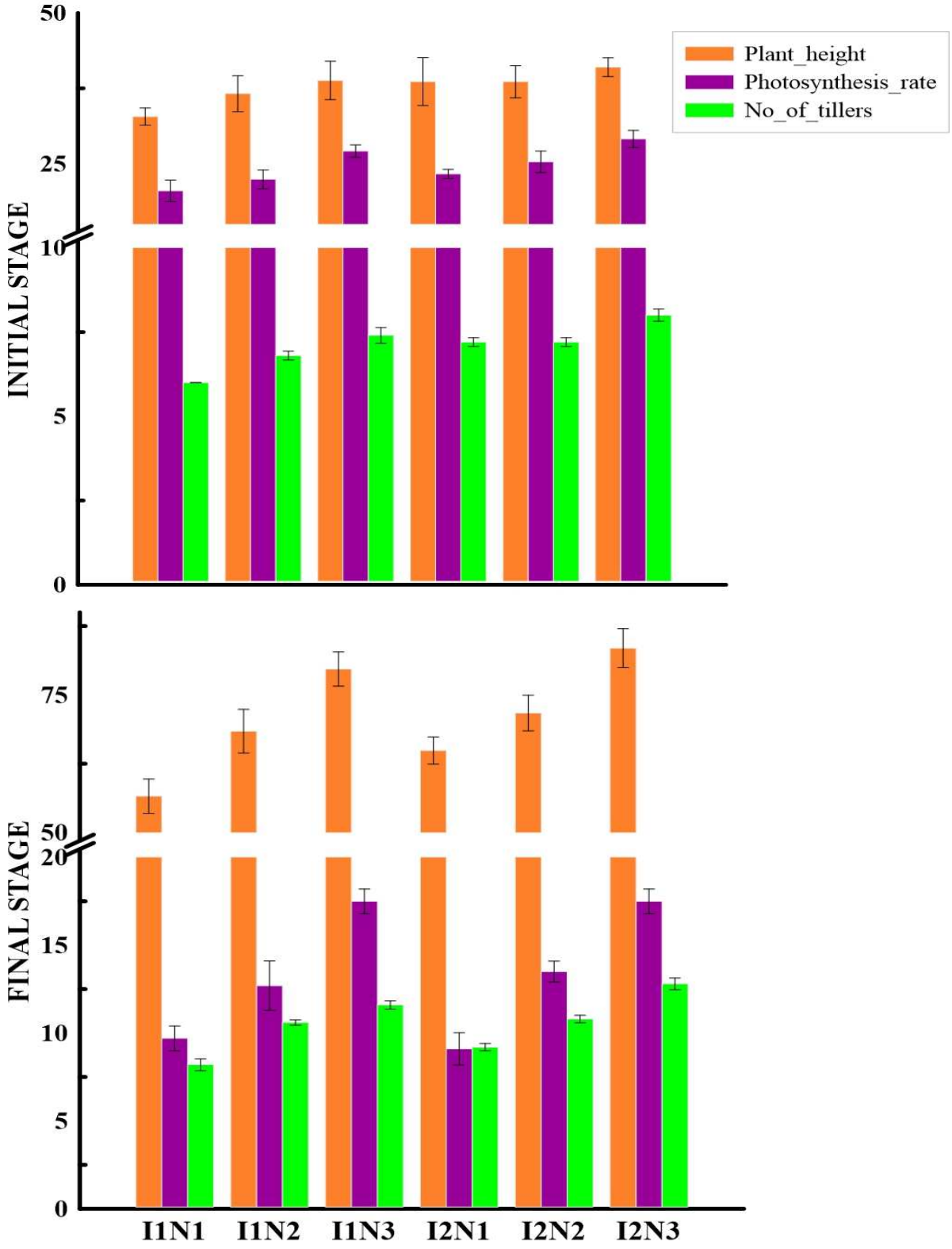


Fig.5.8. Growth characteristics such as number of tillers, plant height, and photosynthetic rate, is represented as Mean ± Standard Deviation (SD) of five replications. Where, I1- 100 % ET_C, I2 – 120 % ET_C, T1- 75 % N- application of inorganic fertilizers, T2- 100 % N application of inorganic fertilizers, T3- 125 % N application of inorganic fertilizer

5.3.2. Yield characteristics

Yield parameters like number of panicles/ tillers, length of panicles/ tiller, number of spikelets/ panicles, number of h0llow spikelets / panicle, number of grains in one panicle, number of filled grains, weight of thousand grains, harvest index and yield recorded at harvest were statistical effected by the nutrient management in this experiment.

Number of panicles/ tiller

The results showed (Fig.5.9) that the number of panicles per tiller in this experiment had a significant effect in nutrient management treatments in this experiment. I2T3 treatment, the highest number of nitrogen administrated treatments, was found to produce the highest number of panicles per tiller compared to other treatments and I1T1 treatment, the least amount of nitrogen administered treatment, had the lowest number of panicles per tiller. This suggests that nitrogen levels play a crucial role in panicle development. Nitrogen, a crucial component in plant growth, stimulates plant development. A 125 % nitrogen treatment increased panicle numbers per tiller. The 100 % nitrogen treatment provided adequate but not optimal nitrogen, while the 125 % treatment promoted greater panicle initiation. Ghosh et al. (2013) had previously reported an increase in panicle number in rice with an increase in nitrogen application which is in agreement with the current study. In rice plants, nitrogen is necessary for the growth of panicles and tillers. It promotes the commencement and development of tillers, which in turn results in the generation of additional panicles and grains. Whereas, water management employed in this experiment failed to exert a significant effect on the number of panicles.

The lack of statistical significance in the impact of irrigation management (100 % ET_C and 120 % ET_C) on the number of panicles per tiller suggests that, within the studied range, water availability may not have been a limiting factor for panicle development. The numerical improvement with 120 % ET_C may indicate a trend toward better performance, even if statistical significance was not reached.

Length of the panicles/ tiller

The results showed (Fig.5.9) that the length of panicles per tiller on this experiment had a significant effect on nutrient management treatments as well as on the interaction effect in this experiment. I2T3 treatment, the highest number of nitrogen administrated treatment, was found to produce the highest number of panicles per tiller, which suggests

that nitrogen levels play a crucial role in determining panicle length (Zhang et al., 2013; Ding et al., 2013). However, the absence of statistical significance in the impact of irrigation management (100 % ET_C and 120 % ET_C) on panicle length, along with the interaction effect, requires careful consideration. The combined impact of irrigation levels and nitrogen application on panicle length is likely additive as suggested by Cao et al. 2017. These factors may interact in a synergistic or antagonistic way, indicating that the simultaneous presence of both water and nutrition management influences the panicle length response.

Number of spikelets/ panicle

The number of spikelets/ panicle of aerobic rice cultivation had no significant impact by the nutrient management treatments as well as water management levels in this particular experiment (Fig.5.9). I2T3 was found to produce the longest panicles per tiller compared to other treatments and I2T2 had the smallest panicles per tiller. However, the numerical improvement with 125 % N application with 120 % ET_C suggests a trend that may permit further investigation or could be indicative of conditions favouring panicle development. High nitrogen availability encourages protein synthesis, which is essential for rice grain development. Increased protein availability has a beneficial impact on the quantity of spikelets, grains per panicle, and panicle filling (Ghosh et al., 2013). As a result, there are more grains overall, which raises the yield.

Number of hollow spikelets/ panicle

The results of a statistical analysis of the data (Fig.5.9) showed that the treatments used throughout the experiment, differing water and nutrient management had a significant impact on the number of hollow spikelets per panicle. Nitrogen levels appear to have an impact on spikelet development, as evidenced by the substantial difference in the number of hollow spikelets per tiller in aerobic rice culture between different nutrient management strategies and the observation of fewer hollow spikelets in the 125 % N application. For grain development, including spikelet formation, nitrogen is essential (Langer et al., 1973; Ansari, et al., 2003). Increased nitrogen concentrations, as seen by the 125 % N treatment, might give the plants enough resources for healthy spikelet development, which decreases the likelihood of hollow spikelets.

Number of grains/ panicle

The number of grains/ panicle of aerobic rice cultivation had a significant impact on the nutrient management treatments in this experiment (Fig.5.10). I2T3 treatment record its highest number of grains per panicle, while I2T1 was used to record the lowest number of grains per panicle. Nitrogen plays a crucial role in the creation of chlorophyll, the green pigment that uses light energy to carry out photosynthesis. Higher levels of nitrogen availability encourage higher levels of chlorophyll, which in turn promotes higher photosynthetic rates and higher grain yields (Guo et al., 2019). With 125 % N in particular, the increased nitrogen levels probably improved overall plant growth and development, leading to more grains per panicle.

However, even though 120 % ET_C had numerically better results, there are a variety of reasons why the impact of irrigation management (100 % ET_C and 120 % ET_C) on the number of grains per panicle did not reach statistical significance. Numerous factors affect the number of grains per panicle, therefore it's possible that the irrigation levels within the tested range had no discernible impact on this particular metric. It's possible that additional irrigation did not significantly boost grain formation since the plants were getting enough water from the 100 % ET_C.

Number of filled grains/ panicle

The number of filled grains/ panicle of aerobic rice cultivation had a significant impact by the nutrient management treatments in this experiment (Fig.5.10). With I2T3 treatment, the highest number of filled grains/ panicle was observed. According to Samonte et al. (1998), rice grain yield was significantly positively impacted by the quantity of filled grains per panicle. Suryaprabha et al. (2011) and Sowmya & Ramana (2012) both showed similar results. The application of nitrogen has an impact on grain quality as well as quantity. However, the application of water management levels had no statistical impact on the filled grains per panicle. Despite the lack of statistical significance, the numerical superiority of 120 % ET_C can point to a trend or a possible beneficial effect that would grow more pronounced in other circumstances or over a longer length of time.

Weight of thousand grains

The weight of thousand grains of aerobic rice cultivation had no significant impact by the nutrient management treatments as well as water management levels in this

experiment (Fig.5.10). The weight of thousand grains is a crucial indicator for evaluating crop production since it offers comprehensive information on the weight and size of individual grains (Ishimaru et al., 2013; Abdipour, et al., 2016). I2T3 was used to record the thousand-grain weight at its highest, while I1T1 was used to record the thousand-grain weight at its minimum. The fact that 125 % nitrogen (N) application and 120 % ET_C had better numerical values for TGW despite not reaching statistical significance suggests that these treatments may have positively influenced grain development and weight. For rice grains to mature, there must be enough amount of water and nitrogen to encourage grain weight and thus grain yield (Sun et al., 2012).

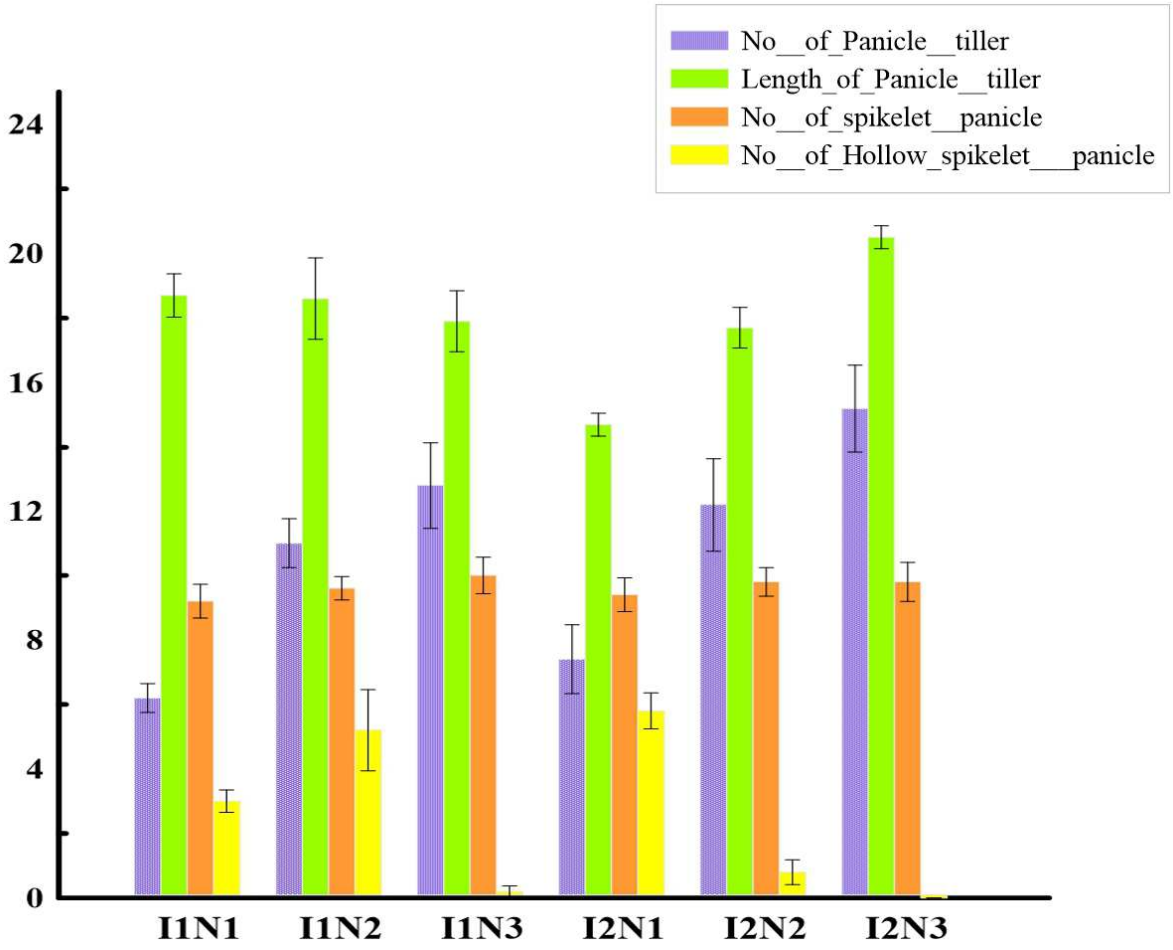


Fig.5.9. Yield characteristics is represented as Mean ± Standard Error (SE) of five replications. Where, I1- 100 % ET_C , I2 – 120 % ET_C , T1- 75 % N- application of inorganic fertilizers, T2- 100 % N application of inorganic fertilizers, T3- 125 % N application of inorganic fertilizer.

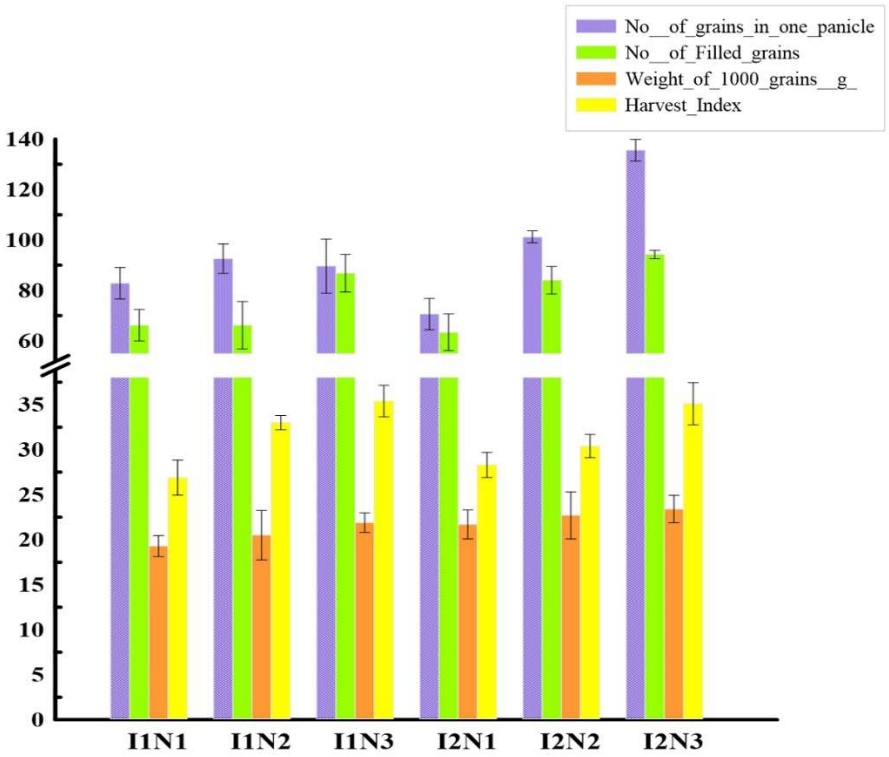


Fig.5.10. Yield characteristics is represented as Mean ± Standard Error (SE) of five replications. Where, I1- 100 % ET_C , I2 – 120 % ET_C , T1- 75 % N- application of inorganic fertilizers, T2- 100 % N application of inorganic fertilizers, T3- 125 % N application of inorganic fertilizer.

Harvest index

A key component of yield-related rice experiments is the Harvest Index (HI), which offers important information about how well resources are distributed between harvested grain and overall plant biomass. Indicating the plant's capacity to transform assimilates into a profitable yield, is a crucial indicator (Wang et al., 2019). In this experiment, the nutrition management treatments had a major effect on the rice harvest index (Fig.5.10). The experiment's I1T3 and I2T3 treatments yielded the greatest harvest index. Bahmaniar & Ranjbar's (2007) study suggests that stabilization of HI over rising N rates is more likely to lead to future yield gains than biological yield growth, which is in agreement with this experiment. However, the application of water management levels had no statistical impact on the harvest index in this experiment. The reduced harvest index might be due to more biomass going toward the vegetative parts or might be due to the pests' attack towards the rice crop.

Yield

The nutrient management treatments significantly affected the experiment's yield. As the amount of nitrogen increased to 125 kg N ha^{-1}, the grain production increased

noticeably (Fig.5.11). In rice, nitrogen has a role in the build-up of carbohydrates in the grain during the ripening stage and in the culms and leaf sheaths during the pre-heading stage (Bahmanyar & Ranjbar, 2007). The application of varying nitrogen levels (75 %, 100 %, and 125 % N) directly influences the nutrient availability for the rice plants. Nitrogen is a crucial element for plant growth, and the higher application (125 % N) likely provided more optimal conditions for the plants, resulting in improved yield. Sufficient nitrogen availability encourages photosynthetic activity, better growth, and ultimately higher grain yield. The lack of statistical significance in the irrigation management results (100 % ET_C and 120 % ET_C) suggests that, within the studied range, the water requirements of the rice plants might have been adequately met even at the 100 % ET_C level.

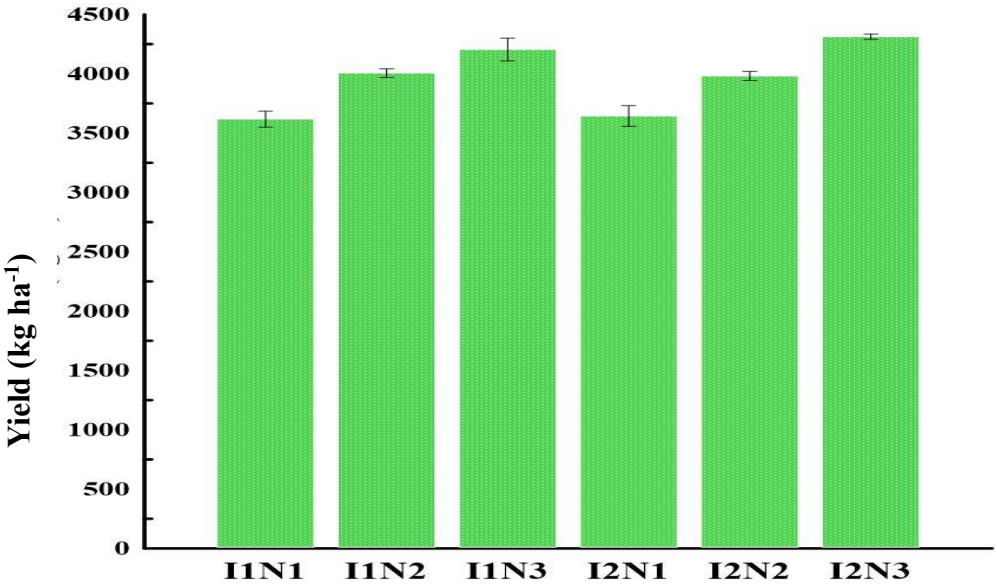


Fig.5.11. Yield is represented as Mean ± Standard Error (SE) of five replications. Where, I1- 100 % ET_C , I2 – 120 % ET_C , T1- 75 % N- application of inorganic fertilizers, T2- 100 % N application of inorganic fertilizers, T3- 125 % N application of inorganic fertilizer.

5.3.3. Relationship study between yield and other yield characters.

The Pearson's correlation was carried out to study the relationship between yield and other yield parameters, specifically like number of panicles per tiller (NP), length of panicle per tiller (LP), number of spikelets per panicle (NS), number of hollow spikelet per panicle (NHS), number of grains in one panicle (NG), number of filled grains (NFG), weight of thousand grains (WTG), harvest index (HI). The obtained data are presented in Fig.5.12. Paddy yield was positively and significantly correlated with most growth

parameters except the number of hollow spikelets per panicle, which is negatively correlated with yield. The number of panicles per tiller, number of grains per panicle, number of filled grains per panicle, harvest index and yield were negatively significantly and synergistically correlated with the number of hollow spikelets per panicle. Previous researchers like Pathak & Patel (1989), Chandra et al. (2008), Ekka et al. (2011), and Sravan et al. (2012) for panicle length and thousand-grain weight; Deosarkar et al. (1989) and Chandra et al. (2008) for the number of grains per panicle; Chauhan et al. (1993), Singh et al. (2000), and Sravan et al. (2012) for harvest index, confirmed the observed positive correlation between grain yield and various traits.

Correlation between yield and harvest index in this experiment could be influenced by several factors related to the complex dynamics of plant growth, resource allocation, and environmental conditions (midland laterite), the correlation seems to be less powerful. Harvest index is the ratio of economic yield to total above-ground biomass, and factors like extreme temperatures can impact the relationship. Also, the timing of measurements, cultural practices, and experimental conditions might also affect the relationship.

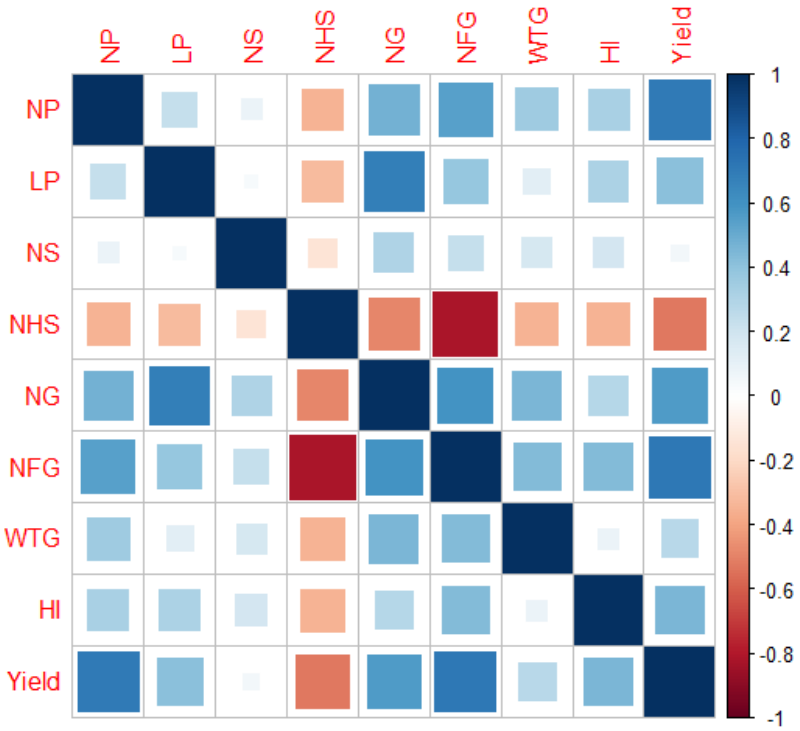


Fig.5.12. Correlation graph between yield and yield characters. The name of each variable is shown on the diagonal, where NP - number of panicles per tiller, LP- length of panicle per tiller, NS -number of spikelets per panicle, NHS- number of hollow spikelet per panicle, NG- number of grains in one panicle, NFG- number of filled grains, WTG- weight of thousand grains, and HI- harvest index HI.

Leaf rolling experiment

5.3.4. Crop biometrics

All the growth parameters were greater in healthy plants and were lower in affected plants. Growth attributes, such as plant height, leaf number, LAI, leaves and stem dry weight, fresh weight and biomass of rice showed a significant reduction under water stress treatments as compared to well-irrigated plants. The availability of optimal water and soil moisture positively influences various plant biometrics in rice cultivation by providing the necessary conditions for growth, nutrient uptake, and photosynthesis. Consistent moisture levels support the development of a robust plant structure, increased leaf area, and overall biomass production, contributing to improved crop performance and yield. Surendran et al. 2021 stated that the growth parameters and yield of aerobic rice may be lower by 20–30 % than the flooded conditions, which is similar to the experimental plots exhibited leaf-rolling in current study.

5.3.5. Soil moisture

Earlier studies revealed that irrigation practices and the texture of the soil play a major role in soil moisture variability (Sugathan, et al., 2014; Surendran et al., 2021). These results confirmed that soil moisture is depleted to a larger extent in the leaf rolling observed plot than in the healthy plants area and this deficit in soil moisture might have affected the growth of the plants (Fig.4.4). Deficit in soil moisture is due to unevenness of the moisture in the lateritic soil of the experimental field. Optimum water supply is essential for normal plant growth and productivity. Continuous or intermittent water stress constrain the growth and performance of cultivated crops more than any other environmental factor (Anupoju & Kambhammettu, 2020).

5.3.6. Relative water content and Membrane leakage

At 30-50 % of RWC turgor had been lost and rice plants showed leaf rolling (Fig.4.5). Plants when exposed to water stress, might evolve a defense strategy as an adaptation measure such as leaf rolling and this will reduce the surface area exposed to radiation and then that will reduce the energy load on the leaf ultimately supporting the plant to overcome the water stress (Chaturvedi, et al., 2012). In a large-scale screening of rice cultivars, the leaf rolling factor under drought stress was found to be one of the best metrics for evaluating degrees of drought tolerance (Pandey & Shukla, 2015; Swapna and

Shylaraj, 2017; Naresh et al., 2018; Manikanta et al., 2020). These results confirmed that the area, where leaf rolling is noticed is due to the water stress observed in the plot because of unevenness of the lateritic soil in the experimental plot which resulted in soil moisture deficit.

Soil amendments improved the moisture content in the soil and thus reduced the water stress condition in the rice plants. The superior qualities of the moisture-absorbing materials, such as maximum organic carbon, and favourable physical properties like water holding capacity (WHC), nutrient retention capacity, total pore space (TPS), etc., maybe the reason for the higher RWC of plants under different soil amendments compared to plants in soil alone and the leaf rolling affected area (Fig. 5.13). These properties will help to maintain the moisture of the soil, which in turn helps to have a higher RWC.

In membrane leakage (ML) also similar results were observed. Incorporation of Moisture-absorbent materials (cocopeat, compost, sawdust and vermiculite) into the soil significantly reduced the ML in plants with soil amendments and the maximum ML, which implies the increased stress level, was recorded in Plants with soil alone and Plant from leaf-rolling affected area (Fig.5.14). The amount of electrolyte leakage is a function of membrane permeability and that gives an indication about the degree of membrane stability. When the plants are exposed to any kind of stress, these cellular membranes will lose their integrity and result in increasing permeability (Blokhina et al., 2003). During stress, membranes are more likely to become 'leaky,' especially in cells with a low saturated fatty acid profile (Scafaro, et al., 2021). These membranes are the primary targets of drought, and they get disturbed as a result of acquired tissue water stress, which can be detected by solute leakage from the damaged tissue (Chaturvedi et al., 2012; Naresh et al., 2018; Manikanta et al., 2020).

RWC and ML are key indicators of the degree of cell and tissue hydration and stress. Water status is pivotal for the optimum physiological functioning and growth processes. Under drought stress, cell membranes are subject to changes such as penetrability and a decrease in sustainability (Pruthvi et al., 2014). The study indicated that the lea- rolled samples which have less RWC and higher ML are under drought stress, they failed to maintain protoplast hydration for a longer span under drought stress conditions.

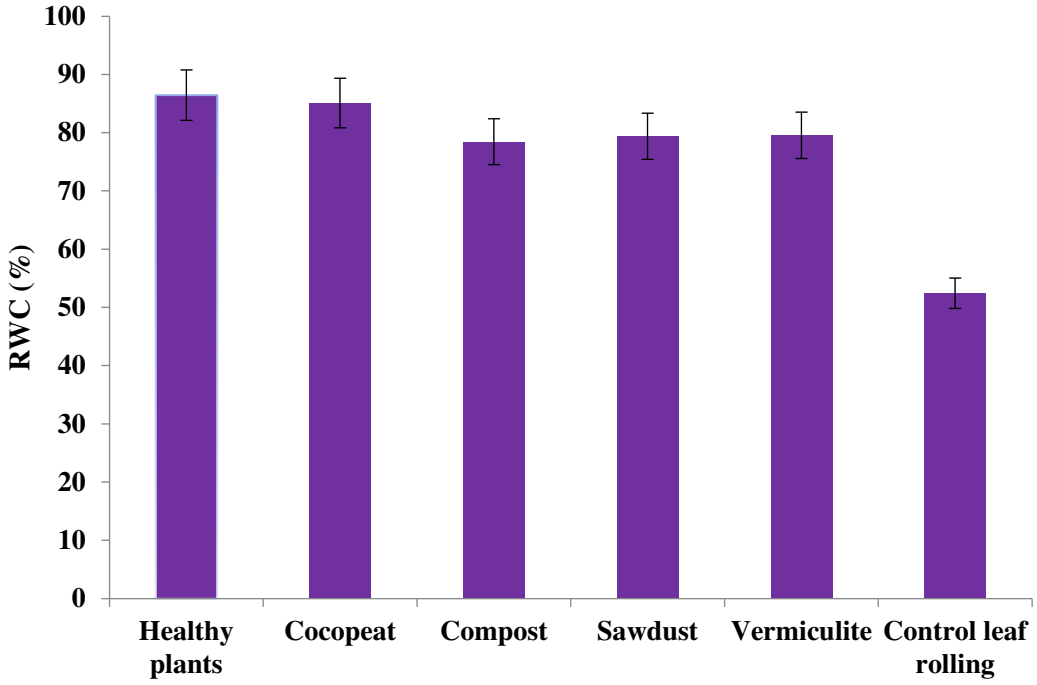


Fig.5.13. Relative Water Content (RWC) of paddy leaves after the incorporation of different moisture absorbent media in the soil.

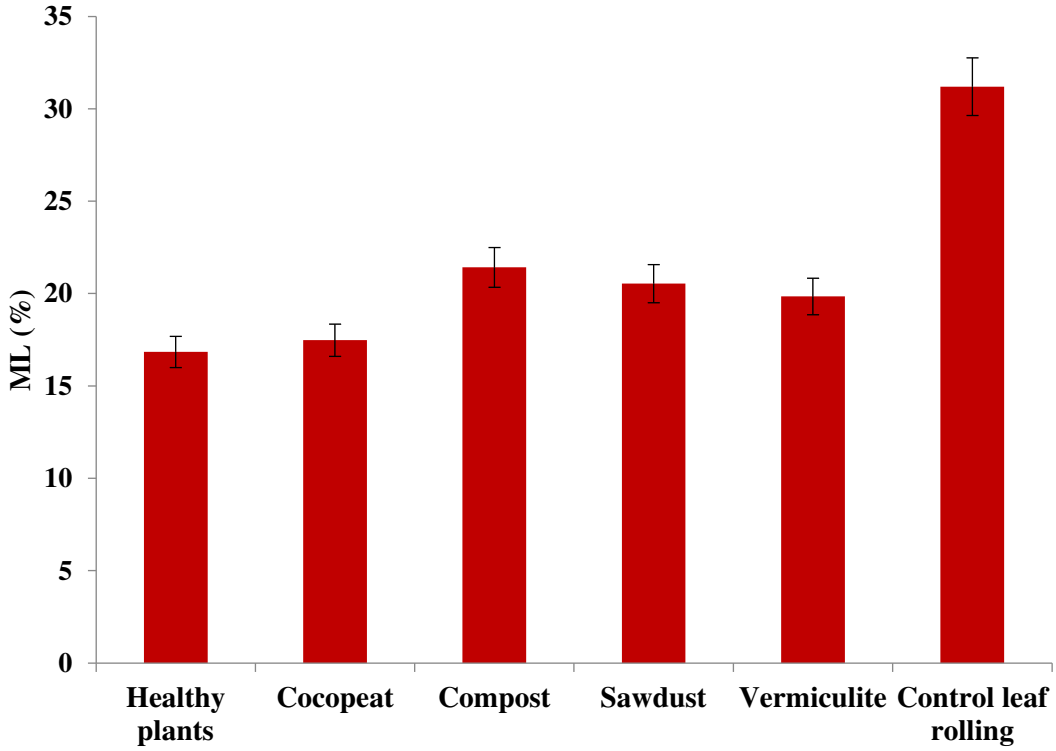


Fig.5.14. Membrane leakage (ML) of paddy leaves for different moisture absorbent treatments

5.3.7. Spectral reflectance and correlation study

Plants experiencing higher stress levels exhibit increased Membrane stability index (MSI), establishing an indirect correlation with various water and vegetation indices, as evident from the correlation analysis in this study (Fig.5.15). Plant physiological processes are intricately linked directly to plant tissue water and indirectly to the soil's water supplying capacity. Relative Water Content (RWC) serves as an indirect variable reflecting crop growth as well as moisture stress. Numerous studies have affirmed the sensitivity of various water and vegetation indices to plant tissue water content, ultimately influencing crop growth and yield. This study further highlights that these spectral indices encapsulate critical information related to crop growth and development, demonstrating predictive capabilities for assessing any kind water stress/ deficit with plants.

Previous research has emphasized the essential role of Leaf Area Index (LAI) in evaluating vegetation water status (Gopinath et al., 2024). In this study, LAI emerges as a key factor for estimating leaf water content through hyperspectral remote sensing. These vegetative and water indices collectively play a pivotal role at the canopy scale, upscaling leaf water content through LAI, effectively presenting crop growth and water conditions in the leaves—findings corroborated in this study. This confirms the potential of spectral values generated using spectroradiometer in identifying various stresses faced by paddy crops, serving as a valuable tool for developing effective management strategies when accompanied by proper machine learning models and algorithms.

Besides, the study also emphasizes that these spectral signatures not only accurately monitor crop water status but also encompass additional information such as chlorophyll, biomass, or LAI and bio chemical constituents (Zhang and Zhou, 2015; Zhang et al., 2015; Gopinath et al., 2024). While RWC effectively reflects crop water stress, obtaining leaf spectral information at turgor using optical remote-sensing techniques can be challenging. Spectroradiometer-derived spectral signatures offer insights into the health status of leaves based on these indices, and the significant positive correlation allows for the estimation of RWC through hyperspectral remote sensing techniques

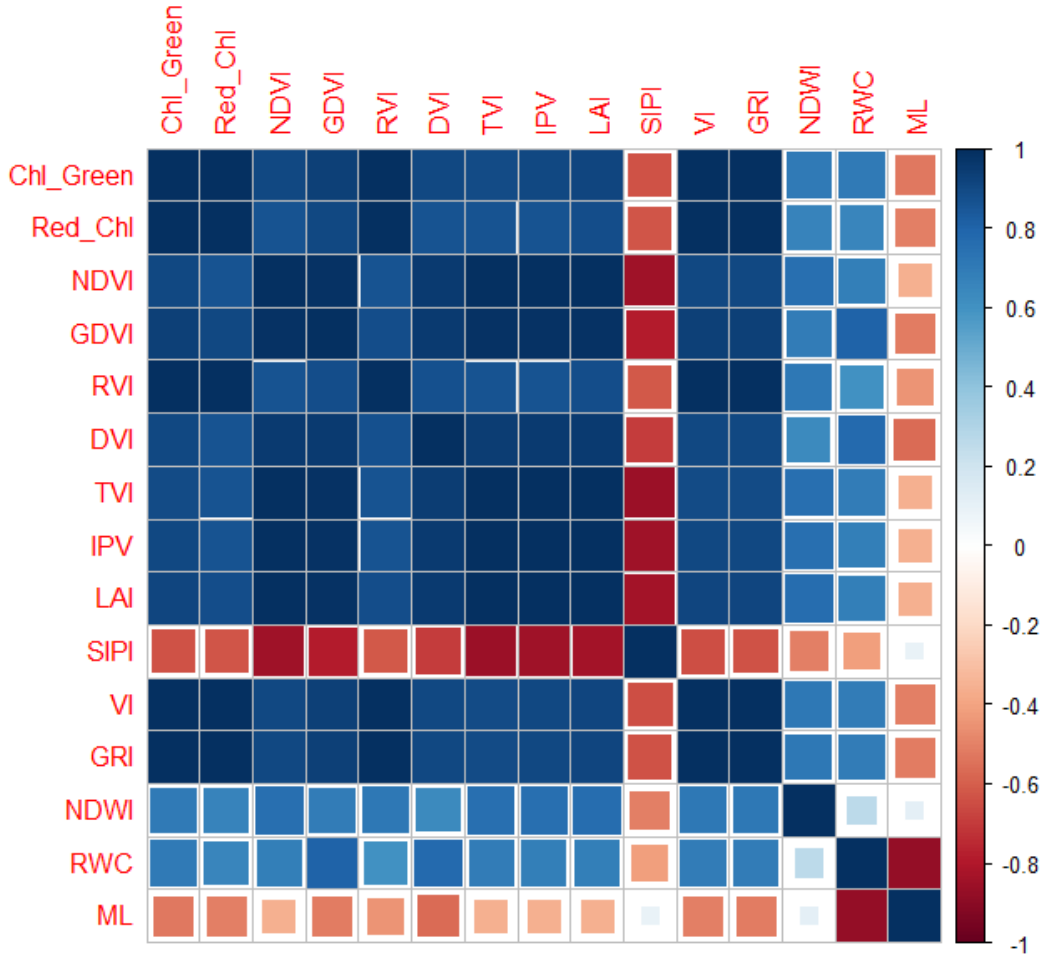


Fig.5.15. Correlation graph between spectral reflectance indices RWC) and ML Where, NDVI- Normalized Difference Vegetation Index; GDVI- Generalized Difference Vegetation Index; LAI- Leaf Area Index; VI- Vegetation Index, RVI- Ratio Vegetation Index/ Simple Ratio; GRI- Green Ratio Index; DVI- Direct Vegetation Index; TVI- Transformed Vegetation Index; Cl(G)- Green Chlorophyll Index; Cl(R)- Red-edge Chlorophyll Index; SIPI- Structure Insensitive Pigment Index; IPVI- Infrared Percentage Vegetation Index; NDWI- Normalized Difference Water Index; RWC- Relative water content; ML- Membrane leakage

Pot culture experiment

5.3.8. Observations

The results suggest that soil containing moisture-absorbent media like cocopeat can reduce leaf rolling and sustain paddy yield in aerobic rice (Reddy, 2019). Results were also in agreement with the present findings. Cocopeat is known for its excellent water retention properties (Noguera et al., 1998; Awang et al., 2009; Hussain & Farooq, 2023). It can hold moisture and release it gradually, providing a more consistent water supply to the rice plants. This helps in preventing water stress, which is a common cause of leaf

rolling in plants. Consistent soil moisture levels contribute to healthier plants and better yields. While cocopeat retains moisture, it also allows for proper aeration of the soil. This is crucial for aerobic rice cultivation, as rice plants need oxygen for their root development. The use of moisture-absorbent media like cocopeat can also help in reducing water evaporation from the soil surface. This is particularly important in aerobic rice cultivation, where water conservation is a key factor.

Cocopeat is a renewable and environmentally friendly substrate, making it a sustainable choice for soil improvement. It is also a byproduct of coconut processing, which helps in utilizing waste materials. It's important to note that the success of using cocopeat or any other moisture-absorbent media depends on various factors such as the specific conditions of the cultivation site, climate, and the rice variety being grown. Additionally, proper management practices, including irrigation scheduling and nutrient management, play a crucial role in maximizing the benefits of these soil amendments.

5.4. Experiment -4

Assessing the influence of different organic management practices on farmer's paddy yield

This experiment was done in the farmers' field with the *Karuna* rice cultivar and was to assess the effect of different organic management practices under common agricultural practices. The results obtained from this experiment are discussed hereunder.

5.4.1 Biometric characteristics

Growth attributes consist of the number of tillers, plant height, LAI, root length, and no. panicles are represented in Fig.5.16. Significant differences were observed in the numbers of tillers, plant height, LAI, root length and number of panicles among treatments.

Plant height

Plant height was significantly influenced by various management practices at all stages of crop growth. Maximum plant height was recorded with the treatment with compost and Azolla along basal nutrients (P4) which was statistically superior to the rest of the treatments at all the stages of crop growth. It might be due to more nutrient availability of P4 plants to attain more height. Compost and Azolla are known to enhance soil fertility by providing essential nutrients, such as NPK, which are crucial for plant growth (Razavipour et al., 2018; Ssenku, et al., 2021). The organic matter in compost improves soil structure and water retention, promoting better nutrient absorption by the rice plants. Azolla, being a nitrogen-fixing plant, contributes to increased nitrogen

availability in the soil (Talley et al., 1977; Ito & Watanabe, 1985; Mandal et al., 1999; Nayak et al., 2004; Akhtar et al., 2020).

Number of tillers

The higher number of tillers/ hill was recorded in treatment with compost and Azolla along basal nutrients (P4). Plants treated with P4 had a better chance of obtaining more nutrients, allowing them to make better use of growth factor to increase the number of tillers per hill. The synergistic effect of compost and Azolla, when applied as part of basal nutrient management, likely contributed to enhanced nutrient availability and soil fertility (Sadegh Kasmaei et al., 2018).

The combined application of compost and Azolla likely created a favourable environment for root development and nutrient absorption, leading to increased tillering in rice plants which is in agreement with Razavipour et al., 2018. The improved nutrient profile and enhanced soil structure created by these organic amendments can stimulate the physiological processes within the plant, resulting in a higher number of tillers. This demonstrates the potential of integrating organic practices like compost and Azolla into basal nutrient management for optimizing rice plant growth and productivity

LAI

The highest values for LAI were recorded in treatment with compost and Azolla along basal nutrients (P4) followed by treatment with the application of Azolla with basal nutrients (P_3), Application of compost with basal nutrients (P_2), and Farmer's traditional management practices (C). The leaf area index was improved by increasing the number of tillers in the P4 treatment, which increased the leaf area that covered the ground area. Because of the rapid root and shoot growth, a high leaf area index is linked to enhanced food assimilation through photosynthesis, resulting in better yield. Hussain et al. (2001) have observed similar findings. Different management practices affected significantly the LAI at all growth stages 30, 60, 90 and harvest stages, as well. Lower growth parameters were recorded under the treatment P1 (Application of basal nutrients only) at all growth phases mainly due to insufficient nutrient supply resulting in a reduction in all growth parameters. Eventually, it led to decline in photosynthesis activity which ultimately recorded the lowest yield. However, all of these parameters were greater in treatment with both the compost and Azolla with basal nutrients and were lower in treatment with application of basal nutrients only.

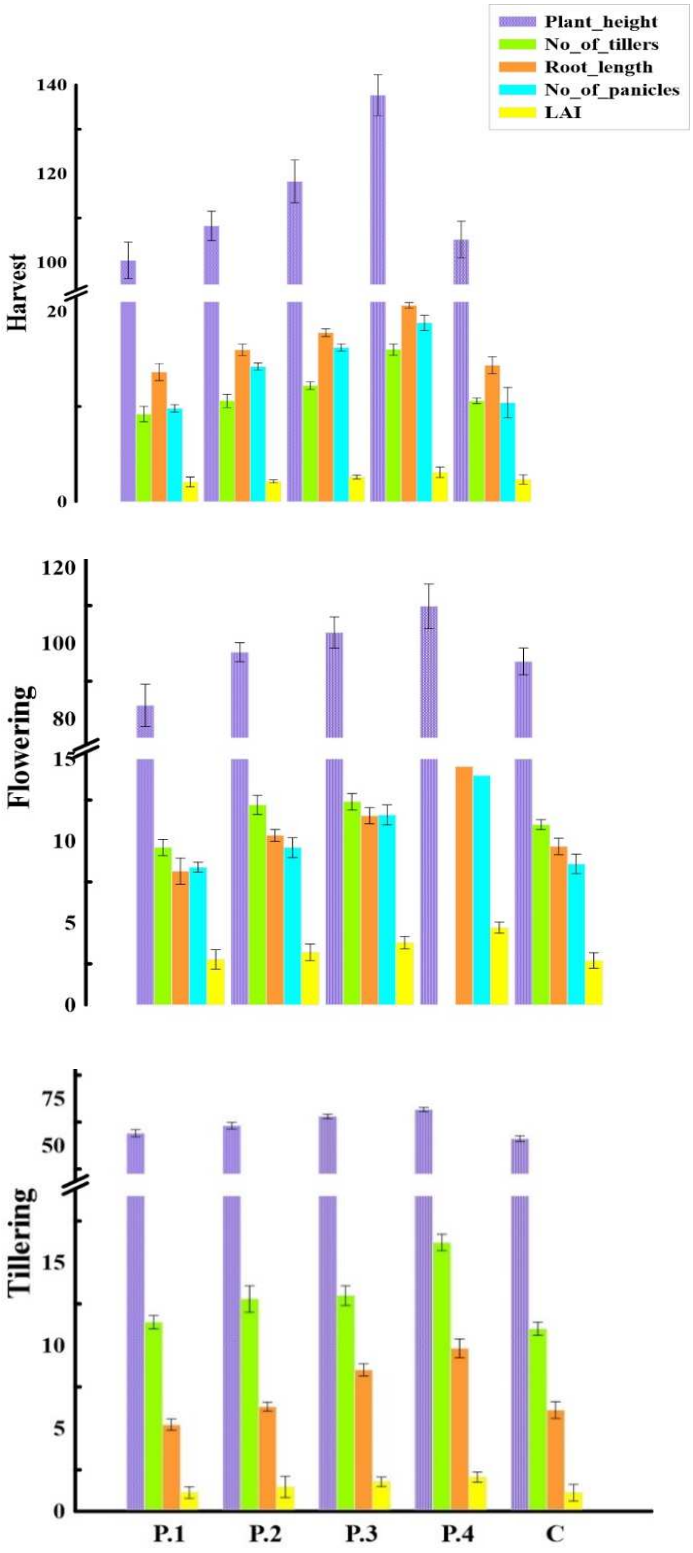


Fig.5.16. Growth characteristics such as number of tillers, plant height, LAI, Root length and number of panicles of the of rice plant *cv. Karuna*, are represented by its value of four replications. Error bar represented as the standard error (SE) of the four replications. Where, P1- Application of basal nutrients only (FYMs); P2- Application of compost with basal nutrients and P3- Application of Azolla with basal nutrients, P4- Application of both compost and Azolla with basal nutrients, and C- Farmer's traditional management practice

5.4.2. Post-harvest soil chemical parameters

Post harvest soil nutrients concentration showed that organic amendments significantly increased soil nutrients concentration (Fig.5.17). The pH of the soil retained in its alkaline nature after in the post-harvest analysis. Combined effect of Azolla and compost treatments applied in the soil during the growing period increases the electrical conductivity (EC) and organic carbon of the soil which is in agreement with results of Abou Hussien et al. (2021). Applications of more Azolla and compost result in higher carbon residue in the soil, which can raise the soil's organic carbon content. This is primarily due to an increase in photosynthetic production and soil rhizosphere distribution, which raises the amount of carbon input into the ground (Satapathy et al., 2015). There were significant variations in the experimental plots' soil available N condition. The experimental plots with fewer organic amendments showed a faster rate of reduction in the soil's available N content. This could be because the rice uptake subsequently removed nitrogen from the soil. This was aligned with the findings of Rahman et al. (2009). Significant difference in the soil available P status of the experimental plots were observed. Since the current Azolla regulates the actual mobilization and release of P, it positively affects the release of phosphorus compounds which resulted in increase the amount of P in the soil (Wang et a., 2019).

The post-harvest soil analysis in the experimental field revels, the available soil potassium, available zinc, available iron, available boron, available calcium and magnesium were not influence significantly by the different organic amendments

Azolla like bio-fertilizers is those containing living cells of different types of beneficial microbes (bacteria, fungi, protozoa, algae and viruses), which play a number of vital roles in soil fertility by releasing nitrogen and P upon decomposition and improve crop productivity and profitability (Saha & Bauddh, 2020. Due to the increase in N concentration in soil treated with Azolla compost implies that these amendments might improve the soil nitrogen and organic carbon status (Singh et al., 2020). The findings further imply that the priming effect of these amendments—increased mineralization of native soil N—was due to the greater proliferation of soil microbes. (Sadegh Kasmaei et al., 2019).

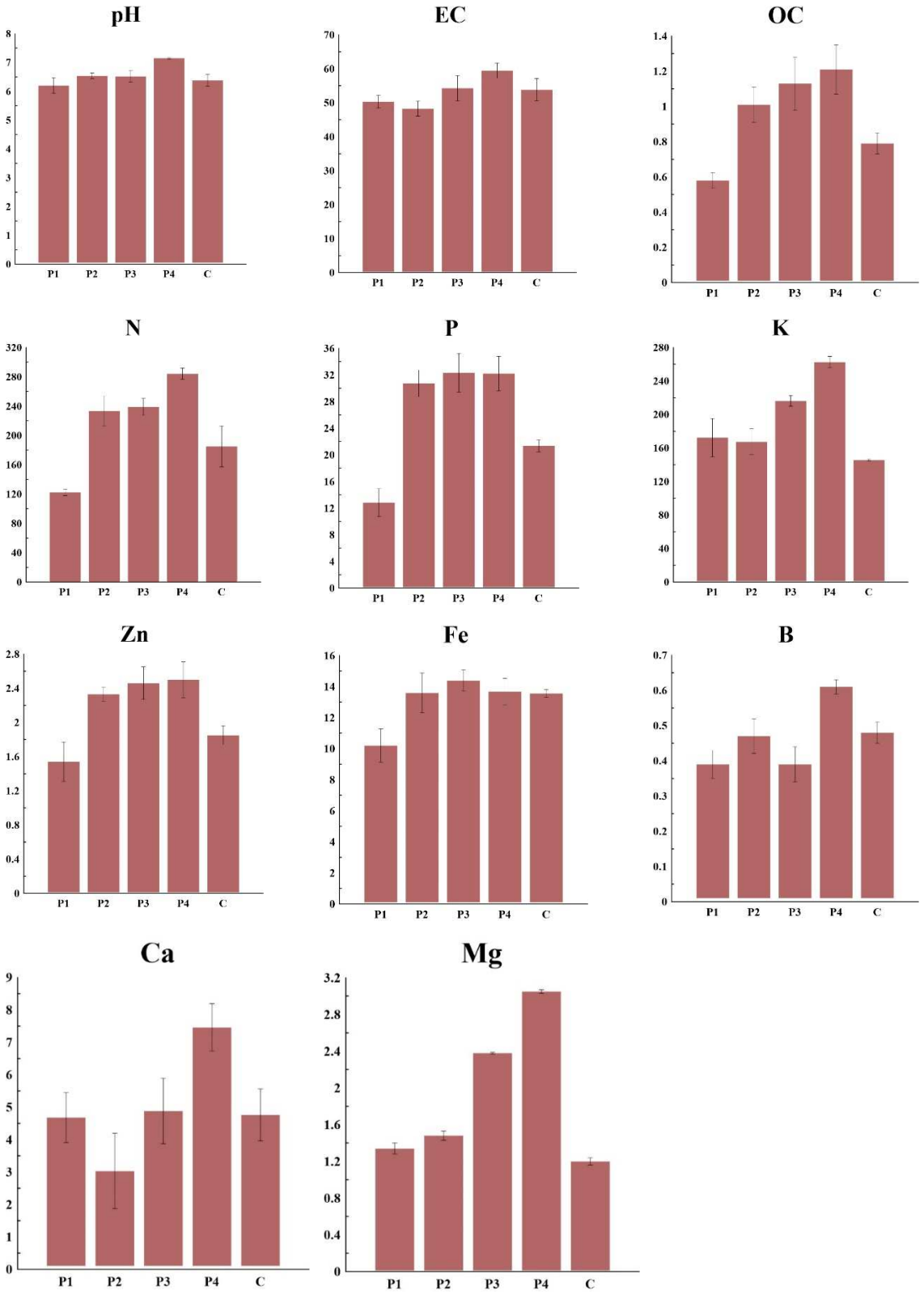


Fig.5.17. Chemical parameters of post-harvest soil are represented by its value of four replications. Error bar represented as the standard error (SE) of the four replications (Were, EC- Electrical conductivity; OC- Organic carbon; N- Nitrogen, P – Phosphorus; K -Potassium; Zn- Zinc; Fe – Iron; B – Bron; Ca – Calcium; Mg – Magnesium)

5.4.3. Yield

The *Karuna* variety treated with Azolla and compost with basal nutrients produced higher 50 % growth and yield parameters than Farmer's traditional management practices. Higher yield under P4 treatment was due to better crop growth and development resulting in to high yield attributes which had direct link on the grain yield. A crucial morpho-physiological characteristic of rice is the number of efficient tillers, which typically rises with rising N rate. Given that the number of tillers per plant and the number of panicles is tightly correlated, the high tillering capacity is a desirable characteristic in the production of rice. Tillering capacity can, to some extent, be used to describe the yield potential of a rice variety (Razavipour et al., 2018). The higher number of panicles per hill in P4 treatments compared to other management practices could explain why this treatment outperforms others in terms of grain yield. A similar result was observed in the study of Subedi & Shrestha (2015). It is obvious that the Azolla biofertilizer significantly improved the rice yield (Yao et al., 2018). According to them, the application of bio-fertilizers such as Azolla and compost improve not just rice productivity but also long-term soil fertility. The increased assimilation translocation from the source to the sink that results from the efficient uptake of N, P, and K may be the reason of the increase in rice grain yield. Furthermore, higher morphological features might be linked to higher yields (Fig.5.18). Furthermore, increased rice grain yield may result from the combination of synthetic fertilizers and high carbon efficiency ratios in the soil (Samarajeewa et al., 2005).

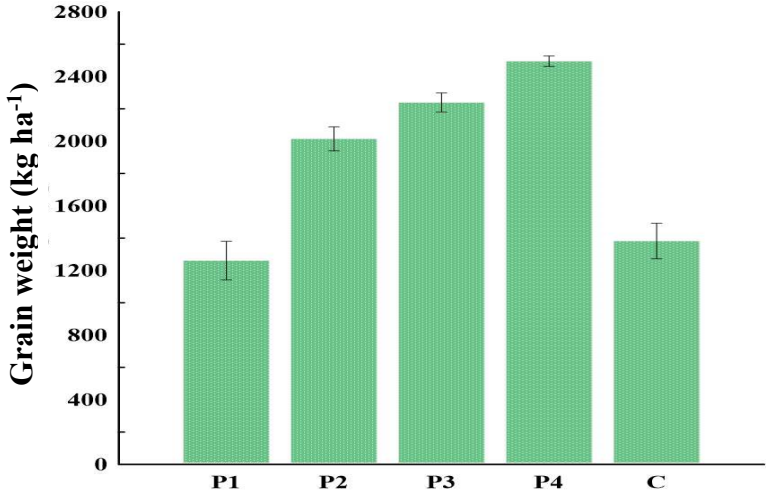


Fig.5.18. Yield of paddy in kg ha^{-1}. Error bar represented as the standard error (SE) of the four replications. Where, P1- Application of basal nutrients only (FYMs); P2- Application of compost with basal nutrients and P3- Application of Azolla with basal nutrients, P4- Application of both compost and Azolla with basal nutrients, and C- Farmer's traditional management practice

5.4.4. Relationship study between yield and soil characters

The relationship study between yield and soil characters were graphically represented in Fig.5.19. According to the current study, the application of Azolla increased the N, OC, and P levels of the soil, suggesting that N and P in the Azolla were released into the soil following its breakdown, these results are in line with Singh & Singh's (1987), Watanabe et al. (1988), Azmal et al. (1997), Singh et al. (2005), and Novair, et al. (2020) findings. By adjusting irrigation, crop residue management, and cultivation techniques, this soil organic N pool can be temporarily managed to satisfy the rice crop's immediate needs (Craswell & Vlek, 1982; Andrews et al., 2021). According to Mahapatra & Patrick (1968), Guppy et al. 2005, Khan et al. 2019, and Li et al. 2023, organic matter used the mechanisms of chelation and reduction to influence phosphorus transformation in wet soil.

Apart from the soil's surface, the plant root zone also has an aerobic-anaerobic interfacial area. This area's neutral pH, low redox potential, and inadequate aeration create a suitable environment for heterotrophic nitrogen fixation (Ponnamperuma, 1972; Rao et al., 1998;). Azolla's addition raised the soil's organic carbon content, which may have improved heterotrophic nitrogen fixers' ability to fix nitrogen. Composts derived from various feedstocks contain portions of organic C and N that may improve soil fertility (Diacono & Montemurro, 2010;Vano et al., 2009) as well as increase enzyme activity and microbial biomass in paddy soil (Ros et al., 2006). As a result, Azolla compost can increase soil microbial activity, which in turn can improve nutrient recycling in treated soil (Jumadi et al., 2014). So, A sufficient amount of nutrients is available to maintain the green leaf area after heading, which in turn promotes photosynthesis and raises grain yields (Yoshida, 1981; Aulak & Malhi, 2005).

Inorganic fertilizers are increasingly used in farming to combat pests and provide plant nutrition. While they seem to improve yield and plant resistance, their long-term effects on soil, microorganisms, human health, and the environment are detrimental. Soil pollution lowers soil biodiversity and fertility, affecting agricultural production. Alternative strategies like biopesticides, bio-remediation methods, plant-associated microbes, and transgenic crop cultivation are effective. Beneficial microbes, such as Rhizobia, Mycorrhizae, Azospirillum, Bacillus, Pseudomonas, Trichoderma, and Streptomyces, help decompose organic matter, increase macro-nutrient availability, and improve crop quality. They also reduce the need for chemical fertilizers, reducing environmental pollution (Bhattacharyya et al., 2016).

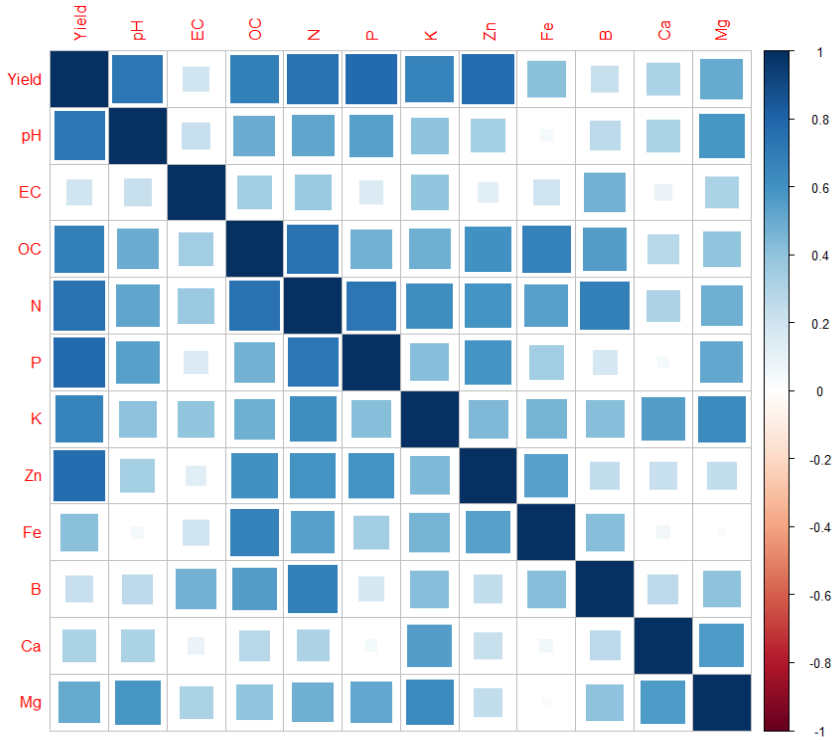


Fig.5.19. Correlation graph between yield and soil characters. Where, EC- electrical conductivity, OC- organic carbon, N-nitrogen, P-phosphorus, K- potassium, Zn- Zinc, Fe- Iron, B-Boron, Ca- Calcium, Mg-magnesium.

5.5. *Experiment -5*

Assessing the effect of different water and straw management practices on decomposition and GHG emission in post-harvest rice fields

This experiment was conducted in the experimental field of IRTA, Spain as a part of the CLIFF-GRADS scholarship programme was conducted to assess the different post-harvest field managements to lower the greenhouse gas (GHG) emissions**.**

5.5.1. Percentage mass loss

The percentage mass loss of rice straw from coarse and fine-meshed litter bags was affected by the water and straw management (Fig.5.20). Flooding conditions enhance methane emissions due to its anaerobic conditions. In the current experiment, WFL accelerates more decomposition than NWF which is in accordance with Devêvre & Horwáth (2000) finding. Because the anaerobes' decomposition ability under flooded conditions was sufficiently high to decompose plant material comparable to that of the aerobes under aerobic conditions (Yadvinder-Singh et al., 2004). But this result is contradictory to the findings of Schmidt et al. (2015) and Tang et al. (2016). According to them aerobic condition accelerates more straw decomposition.

In the present study, along with the water and timing of straw management litter bags with smaller (fine) mesh sizes, undergo more decomposition, and higher mass loss, than in coarse meshed bags. This is contradictory to the findings of Schmidt et al (2015, 2016b) and Widyastuti's (2003), in which loss of mass in coarse-meshed bags was higher than in fine-meshed bags under similar conditions. This may be due to the priming effect of straw inside the litter bags. The priming effect is often explained as an increased microbial activity resulting from the higher availability of soil organic matters (SOM) in a noticeably brief period (Fontaine et al., 2003).

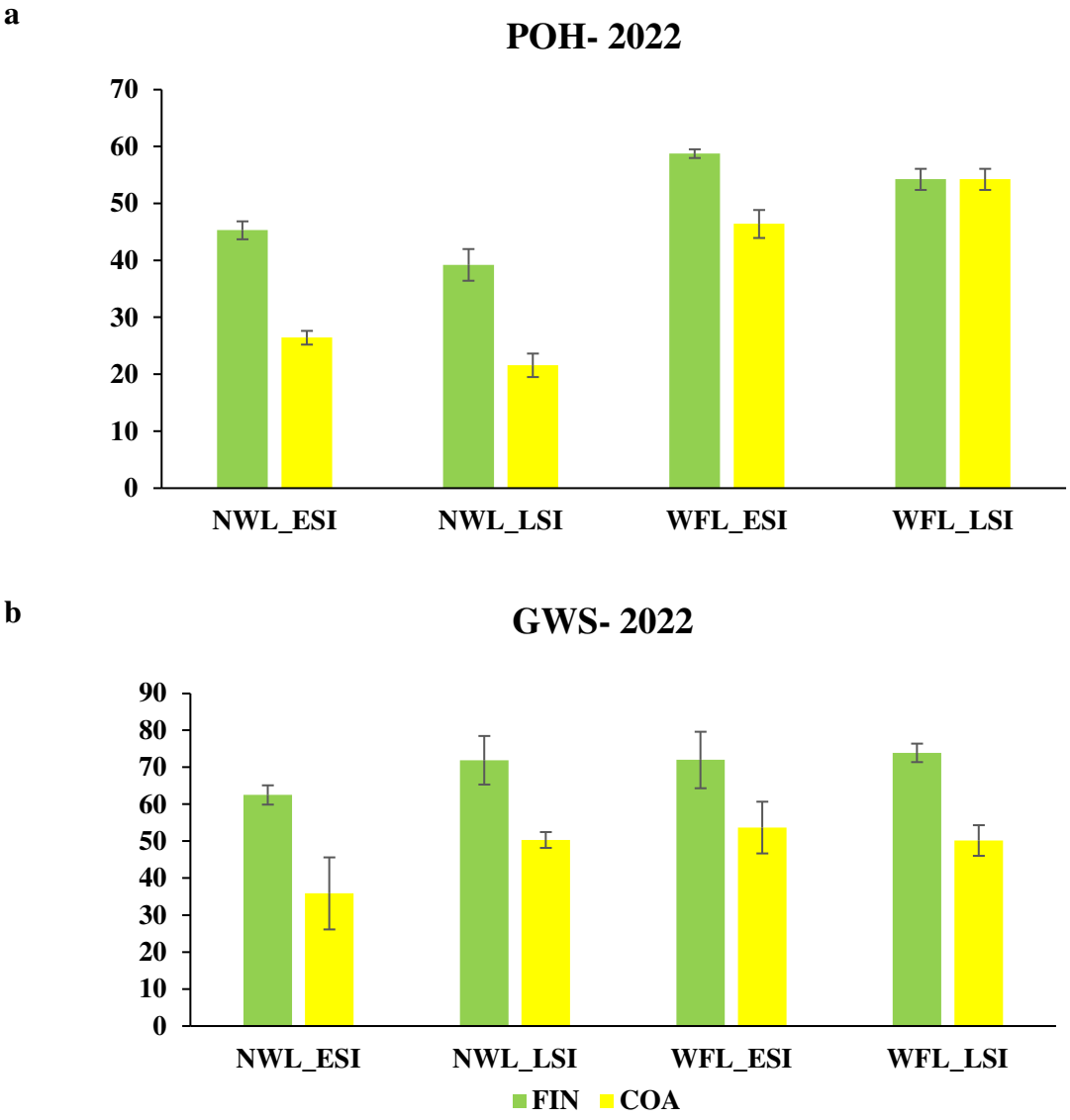


Fig.5.20. Percentage mass loss of the straw bag after decomposition during the post-harvest season and growing season in 2022 a fine (FIN) litter bags and coarse (COA) litter bags (NWF ESI- Non winter flooding with early straw incorporation; NWF LSI- Non winter flooding with late straw incorporation; WFL ESI- Winter flooding with early straw incorporation; WFL LSI- Winter flooding with late straw incorporation).

5.5.2. Decomposition rate

The mass remaining at extractions from non-flooded treatments (NWF) was more than in the flooded treatments (WFL). WFL accelerates decomposition more quickly than NWF conditions. Hence, the decomposition rate constant of litter bags under NWF treatments was less when compared to the same of WFL treatment (Fig.5.21), which is consistent with the findings of Devêvre & Horwáth (2000). On the other hand, the mass remaining in LSI treatments was more than ESI. This denotes that the litterbags from LSI tend to retain their mass or in other words, the samples from LSI tend to undergo less or minimum decomposition process than the samples from ESI. The impact of the environment is responsible for this. By delaying the addition of straw until December, you can stop or slow down the rate of decomposition by lowering the microbial activity in the soil because of the onset of winter (Sorensen et al., 2018). However, the addition of straw accelerates the rate of decomposition by adding a carbon source, which ultimately increases the production of methane, especially in the late October and early November period when soil bacteria are most active (Wessén & Berg,1986). This again states that the ESI management practice promotes more decomposition whereas LSI management contributes to less decomposition.

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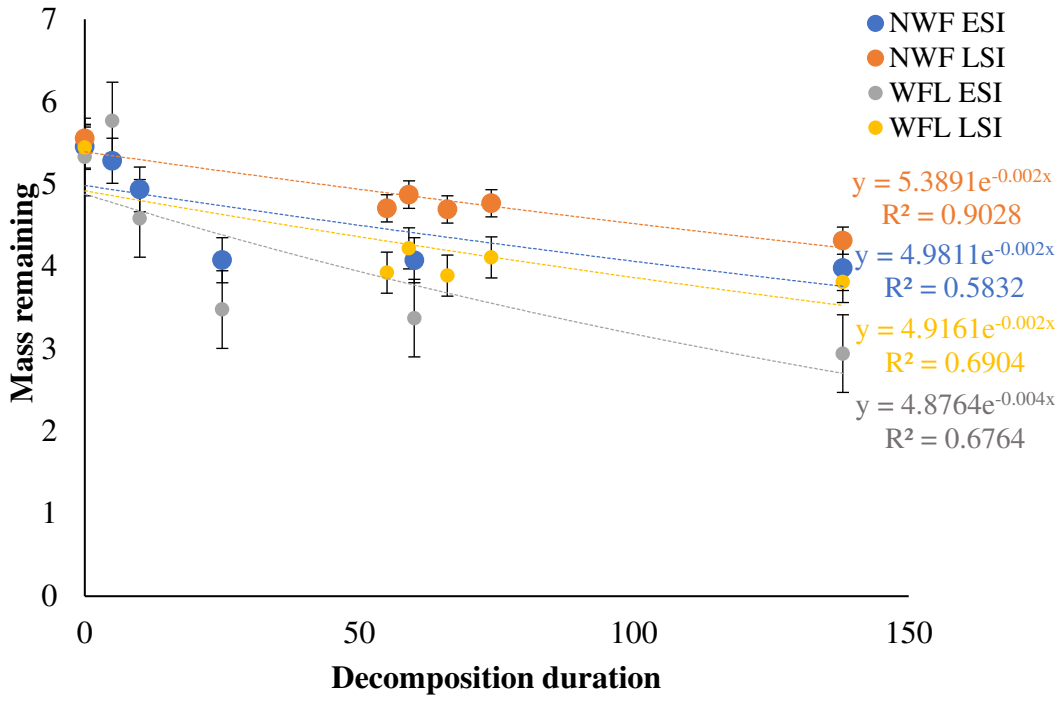

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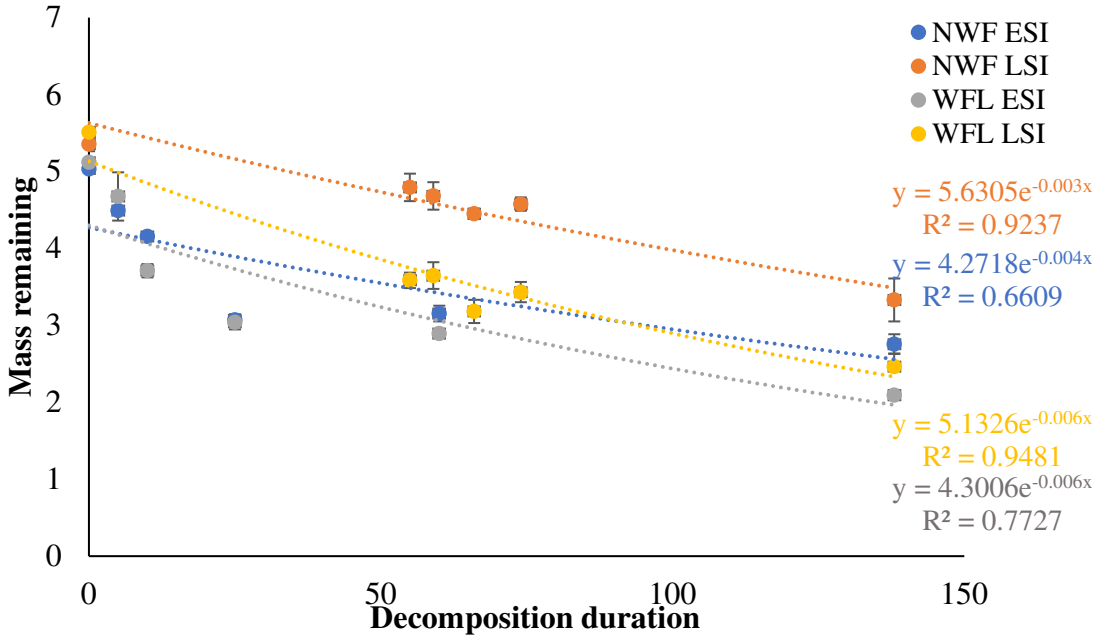

Fig.5.21. Decomposition curves of fine and coarse straw bag at five extractions (E1, E2, E3, E4, & E5) during the post-harvest season in 2017 (a) Coarse litter bags (b) fine litter bags (NWF ESI- Non winter flooding with early straw incorporation; NWF LSI- Non winter flooding with late straw incorporation; WFL ESI- Winter flooding with early straw incorporation; WFL LSI- Winter flooding with late straw incorporation).

5.5.3 Methane emissions

The emissions of methane (CH_4) in the post-harvest are influenced by the management of winter flooding and the timing of straw incorporation (Fig.5.22). The practices examined in this study have significant implications for greenhouse gas emissions in paddy fields. The incorporation of straw serves as a source of organic carbon, while the moisture and temperature of the soil regulate the processes of mineralization (Devevre & Horwath, 2000). These processes, as observed in this study, are affected by the management of water and the timing of straw incorporation. During the post-harvest season, the highest emissions were observed in flooded fields with early straw incorporation (WFL ESI treatments). Dry fields during the winter season greatly reduced post-harvest CH_4 emissions due to the fact that methanogenesis occurs under anaerobic conditions. Delaying the incorporation of straw from October to December resulted in a significant decrease in post-harvest CH_4 emissions, likely due to a drop in soil temperature to 9 °C, which is below the optimal range for methanogenesis (Fey et al., 2004; Fey & Conrad, 2003).

The substantial reduction in CH_4 under non-flooded conditions can be accounted for the exponential response of methane emissions to temperature, as explained by Camacho et al. (2017). The occurrence of the CH_4 peak, immediately after the introduction of straw in November (Fig.5.23) aligns with the lag phase time of methanogenesis described by Fey et al. (2004). This finding suggests that the management of WFL-ESI in the rice field provided the optimal conditions for methane formation. This could be due to a deficiency of readily available soil organic carbon content or because the carbon was protected in organo-mineral complexes, as proposed by Wang et al. (2009).

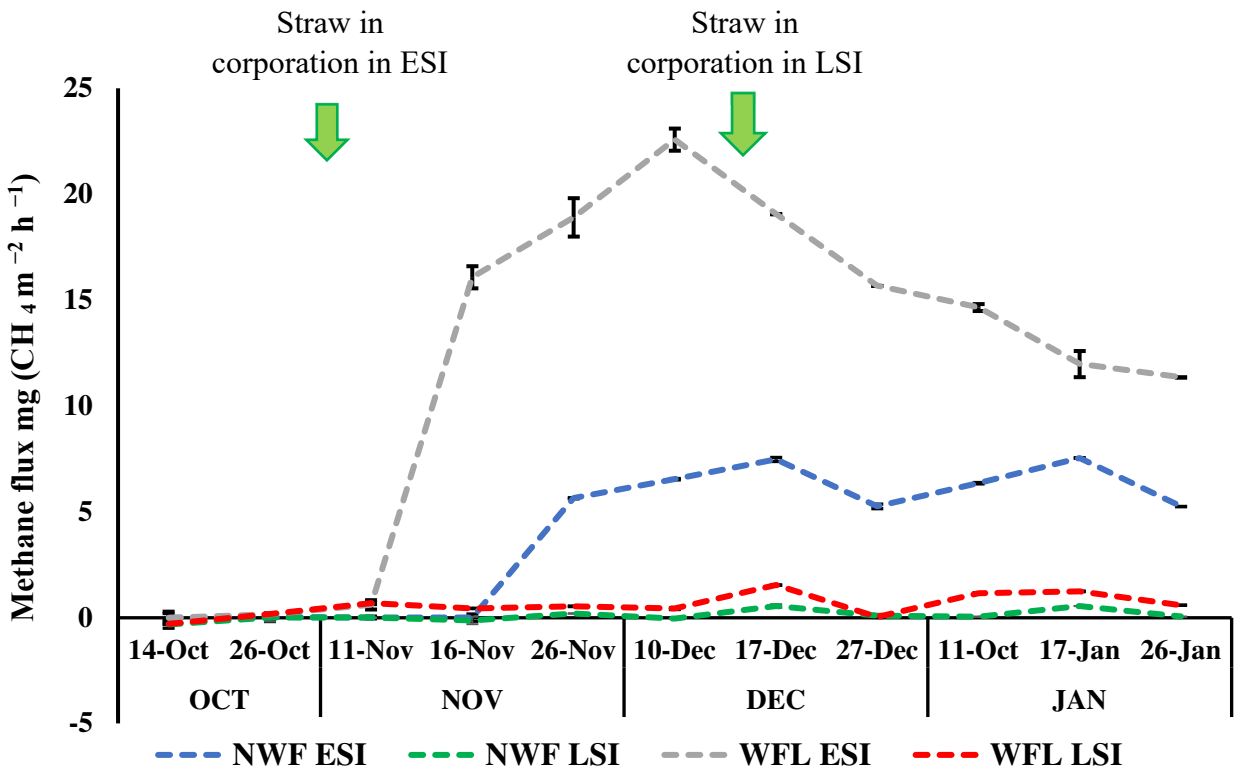

Fig.5.22. Methane flux during the post-harvest season of 2022 under different water and straw management (NWF ESI- Non winter flooding with early straw incorporation; NWF LSI- Non winter flooding with late straw incorporation; WFL ESI- Winter flooding with early straw incorporation; WFL LSI- Winter flooding with late straw incorporation).

In the context of climate change, the outcomes of this study underscore the ecological and environmental benefits of adopting site-specific post-harvest field management practices. By favouring non-winter flooding and late straw incorporation, not only can farmers potentially reduce GHG emissions, but they may also contribute to

climate change mitigation efforts. These sustainable practices present an environmentally conscious approach to agriculture, promoting resilience in the face of evolving climatic

5.6. Experiment- 6

The results acquired from the research work entitled "*Calibration and validation of crop simulation model -DSSAT and temperature sensitivity analysis"* were collected and elucidated. This experiment was conducted to understand the application of crop simulation model, DSSAT, for water and nutrient management on yield of rice under different climatic scenarios and to understand the impact of temperature on rice yield with sensitivity analysis using DSSAT model.

5.6.1 Calibration and Validation of Crop Simulation Model- DSSAT

DSSAT CERES-Rice was used to simulate rice development and yield. Three stress-free treatments (P1T1, P1T2, P2T1, and P2T2) from the experiment conducted in 2019 and 2020 were used to calibrate and validate the genetic coefficients. The values for genetic coefficients were established for *Uma* rice verity under aerobic rice cultivation for midland and upland areas. The measured and simulated number of days taken to physiological maturity (PMD) was on par during 2019 and 2020 experiments. The simulated and the observed data as given in Fig.5.23 revealed deviation within – 4 to + 4 days between observed and simulated days taken to attain maturity in different treatments during in both 2019 and 2020. The results simulated for leaf area index and yield revealed that the observations were matched closely with observed LAI and yield for all the treatments. A comparison between observed and simulated values for leaf area index and yield are presented graphically in Fig.5.24 and Fig.5.25. The results revealed that simulated leaf area index and yield were matched closely with observed values for all the treatments. It is therefore feasible to simulate rice yields in aerobic systems for the midland and upland regions of Kozhikode under different planting, irrigation, and nitrogen conditions using the latest version of DSSAT-CERES-Rice (V4.7). Vysakh et al. (2016) conducted a field experiment in Thrissur, district used two rice varieties (*Jaya* and *Jyothi*) and five planting dates to simulate phenology and grain yield using CERES-Rice model, but overestimated rice cultivars' grain yield, requiring further refinement.

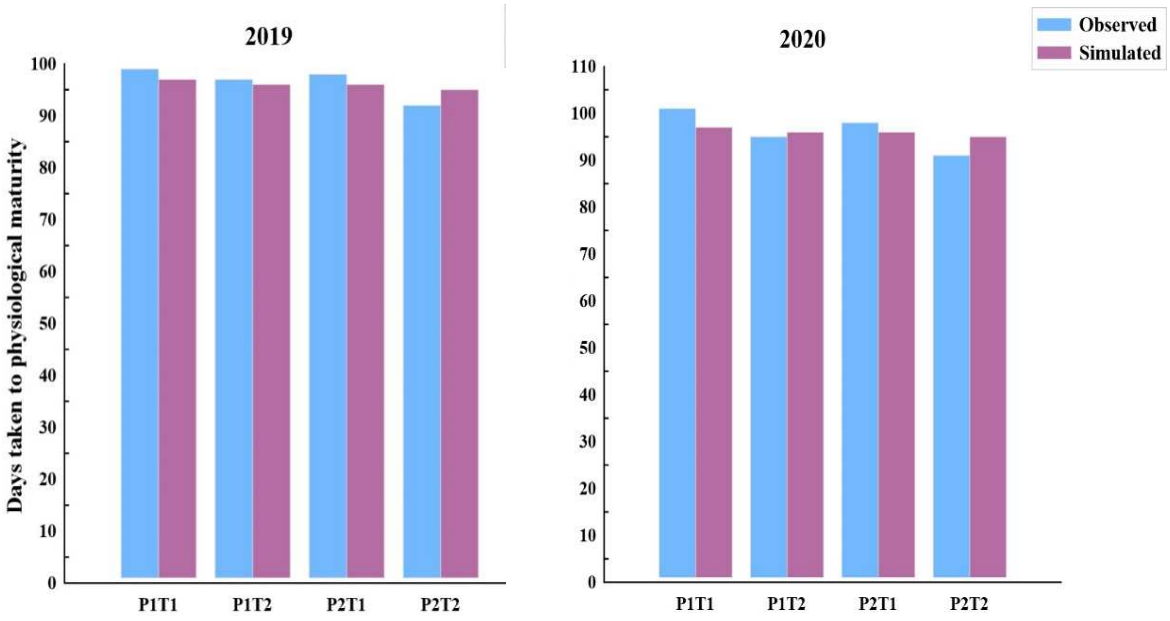

Fig.5.23. Number of days taken to attain physiological maturity in different treatment during 2019 and 2020 experiments. Where, P1- DSR, P2- Transplanted, T1 is 125 % of inorganic fertilizers, and T2 is 100 % of inorganic fertilizers

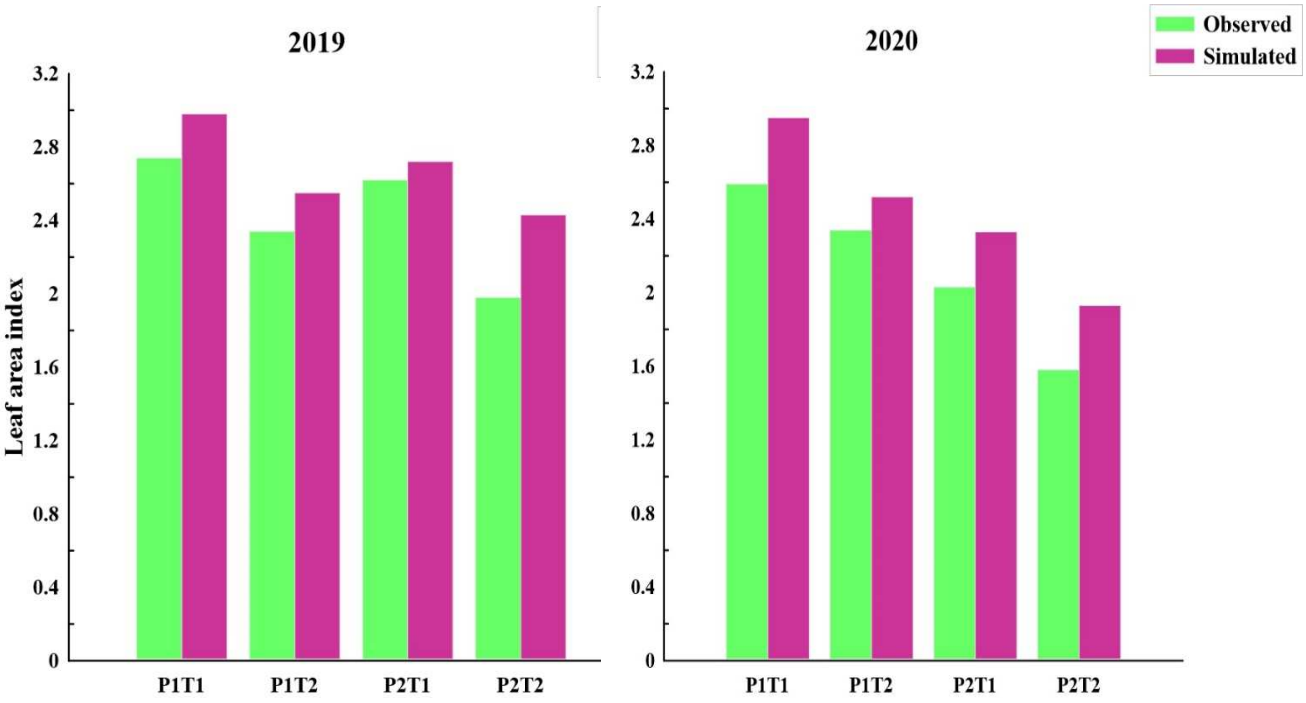

Fig.5.24. Leaf area index (LAI) calculated in different treatment during 2019 and 2020 experiments. Where, P1- DSR, P2- Transplanted, T1 is 125 % of inorganic fertilizers, and T2 is 100 % of inorganic fertilizers

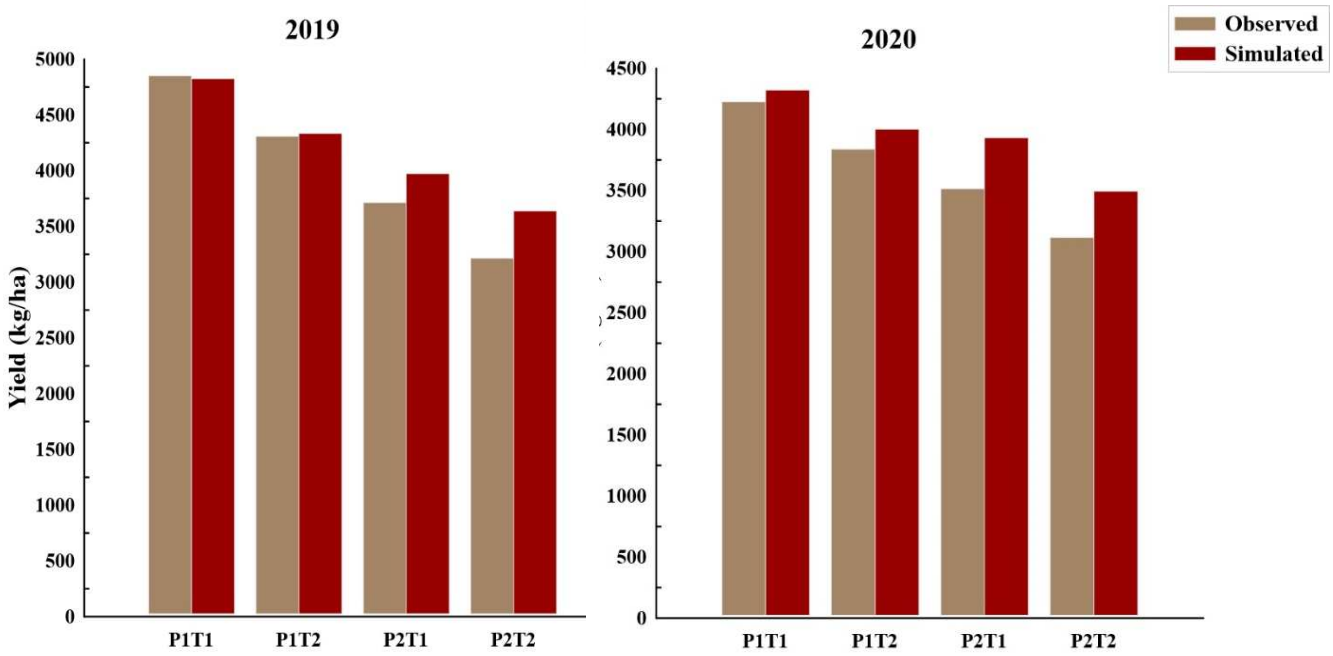

Fig.5.25. Yield (kg ha^{-1}) calculated in different treatment during 2019 and 2020 experiments. Where, P1- DSR, P2- Transplanted, T1 is 125 % of inorganic fertilizers, and T2 is 100 % of inorganic fertilizers

The study by Alejo (2020), used the DSSAT-CERES-Rice model to evaluate climate change's effects on aerobic rice production. Results showed the model can accurately simulate crop and nutrient management strategies, and guide long-term climate change adaptation and mitigation plans. Singh et al. (2007), Ray et al. (2018), Jha et al. (2020), and Lu et al. (2022b) conducted many studies using the DSSAT rice model to determine the optimum management methods specific to their environmental conditions and to increase rice production for different rice varieties. Their findings demonstrated that the CERES-Rice model, which had a positive D index, a low n RMSE, and a high correlation coefficient between the simulated and observed similar as in the present study, had an excellent simulation effect on the yield. Site specific management practices improve the results by balancing every possible component (input data) and it reflects in the good yield prediction.

5.6.2. Model simulation under the temperature sensitivity analysis

Climate change will be one of the deciding variables affecting global food supply in the future since crop development is very susceptible to variations in climatic circumstances. Because rice is a staple food for Keralites, it is critical to understand the effects of climate change on the country's rice production.

Simulation studies in this current experiment showed that, paddy yield production (in kg ha^{-1}) was predicted by calibrated DSSAT software under different temperature sensitivities (with 0.5^0 C, 1^0 C, and 1.5^0 C increments for the maximum and minimum temperatures both separately and together of 2019 climate data) were significantly affect the production and was compared with simulated yield for calibrated model for 2019 field experiment. Initially, in all four treatments, rice yield was projected to increase with 0.5^0 C and 1.0^o C temperature increment both maximum and minimum temperatures, then a sharp decline in the yield was predicted for scenario with 1.5^0 C increase in both minimum and maximum temperature (Fig.5.26 A). 16.3 % to 31.1 % of yield loss was predicted among different treatment under the scenarios with 1.5^0 C increase in both maximum and minimum temperature. But rice yield predicted for scenarios with 0.5 ^{0}C, 1.0 ^{0} C and 1.5 ^{0}C increments in maximum and minimum temperature separately for all four treatments showed increase in yield, which seems to be positive when comparing with the yield simulated for 2019 experiment (Fig 5.26 B & C).

Similar with the present study, Ray et al. (2018) and Basak et al. (2010) have been also discovered that increases in the daily maximum and minimum temperatures beyond a level tend to decline the yield. Dias et al. (2016) results are also aligned with present study which show that changes in temperature and solar radiation, combined with less rainfall, affect rice growth and yield. Grain yield in both varieties is declining by 25 % to 35 %.

Rice cultivation is sensitive to temperature changes, which can negatively impact yield due to various factors. High temperatures can decrease photosynthesis, increase respiration rates, reduce pollen viability, cause sterility and spikelet fertility, shorten the growing period, increase vulnerability to pests and diseases, and constrain water availability (Fahad, 2019). The specific impact of temperature on rice yield can vary depending on the rice variety, local climate conditions, and cultivation practices. Climate change and global warming may exacerbate these challenges, making it crucial for agricultural practices to adapt to changing environmental conditions. Therefore, it is essential for agricultural practices to adapt to changing environmental conditions**.**

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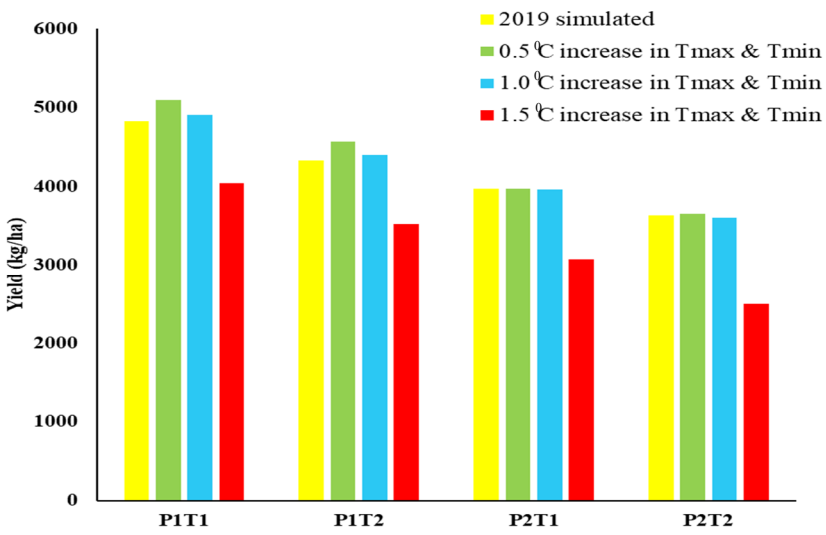

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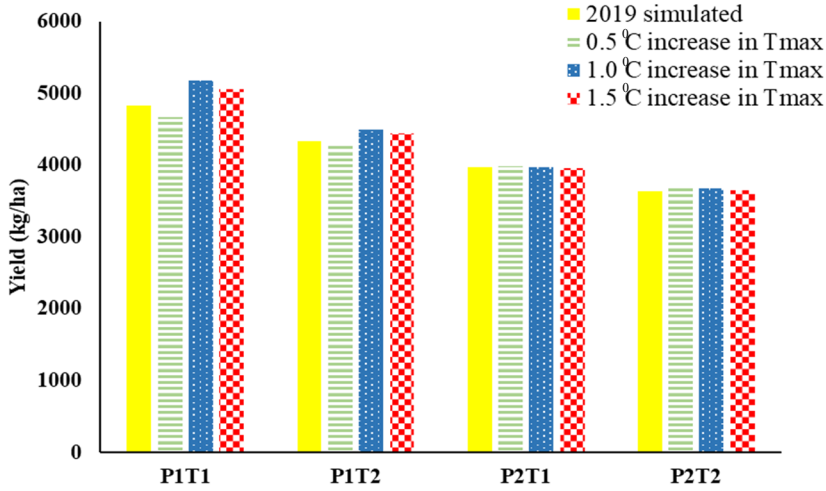

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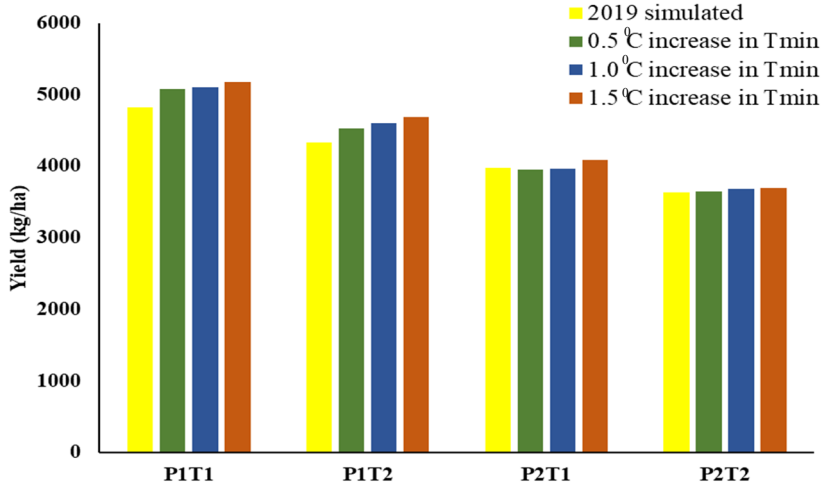

Fig.5.26. Yield simulations in different treatment under different temperature sensitivity scenarios. Where, P1- DSR, P2- Transplanted, T1 is 125 % of inorganic fertilizers, and T2 is 100 % of inorganic fertilizers

5.7. Experiment -7

The results acquired from the research work entitled "*Suitability analysis and rice yield prediction for Kozhikode and Palakkad districts under future climate scenarios"* were collected and elucidated.

This experiment was conducted to identify the potential areas appropriate for rice production through suitability analysis and yield predictions for Kozhikode and Palakkad district under future climate scenarios.

5.7.1. Paddy suitability

Paddy is suitable for 48 % of the Kozhikode district area, whereas 3% of the land is highly suitable for paddy production. In the case of Palakkad district's land, namely 96 %, is suitable for paddy farming. The remaining portion is classified as marginally appropriate (0.86 %) or inappropriate (1.36 %) because of soil and environmental problems that make rice farming unfeasible. The area of each class, however, is assumed to fluctuate based on variations in soil characteristics, rainfall, water availability, and other related factors (Singh et al., 2019). A similar study by Raju et al. (2022) mapped the rice fields in Kerala's Palakkad district using remote sensing and geographic information systems (GIS). Using administrative boundaries and Sentinel-2 data, the area was estimated to be 24742.76 ha, with an accuracy rate of 88.33 % on average. According to Chandrakala et al.'s 2019 study, there is around 14.79 % of very suitable land for paddy production in Kerala's Idukki district. Simultaneously, AbdelRahman et al. (2016) projected that the mountainous and sloping upland lands in the Chamarajanagar district of Karnataka, India, would always be unsuitable because of extremely severe drainage and slope limits.

Overall, the results and discussion of the paddy suitability map of Kozhikode and Palakkad districts using the AHP method can provide valuable insights into the suitability of different areas in the district for paddy cultivation. To determine which locations are ideal for rice farming, it incorporates a number of spatial variables. By highlighting areas that are particularly favourable for growing paddy, the map can help guide agricultural planning and decision-making in the district, ultimately contributing to the sustainable development of the agricultural sector in Kozhikode and Palakkad districts.

5.7.2. Yield estimation

The results of the study showed that climate change is likely to have a negative impact on paddy yield in the Palakkad and Kozhikode district, as projected paddy yields for future scenarios were decreased across all four climate models considered (CMCC-ESM2, EC-Earth3, EC-Earth3-Veg, and GFDL-CM4) for the years 2025 to 2100 under both the SSP 2 – 4.5 and SSP 5 – 8.5 scenarios, with a corresponding increase in temperature. However, in current yield estimation, there was evidence of both overestimation and underestimate. The reduction of rice yield in future climatic scenarios might be due to the elevated temperatures proposed by the climate models which is higher than the suitable temperature range of rice crop as evidenced from the previous experiment.

The study by Lin & Jain (2022) reported, rice production is expected to decline by 14.5 % to 1.1 by the end of the 21st century due to climate change and elevated CO_2 levels. The study uses a global land surface model, ISAM, driven by CMIP6 projections to estimate rice yield and production in South and Southeast Asia which was similar with current predictions. In order to anticipate the future climate of central Kerala, Aswathi et al. (2022) used the ECHAM and GFDL-CM3 models based on RCP 4.5 and RCP 8.5. They also evaluated the CERES Rice model. The decrease in yield was attributed to rising temperatures and increased precipitation.

This suggests that climate change is likely to lead to a decline in agricultural productivity, posing significant challenges for food security in the region. Therefore, it can be inferred that the projected impact of climate change on paddy yield in the Palakkad and Kozhikode district is consistent across all the five climate models considered under both the SSP245 and SSP585 scenarios.

5.7.3. Adaption strategies for improving the rice production using DSSAT model

Growing paddy, which serves as many farmers' primary source of income, is one of the most important agricultural practices in the state. However regional paddy farming is severely endangered by rapidly changing climate trends, which include increased temperatures, changed rainfall patterns, and a rise in the frequency of extreme weather events. Identifying the suitable adaptation strategies to improve the yield with respect to local environments under the climate changing scenarios is crucial. The DSSAT modelling

system may prove to be a valuable instrument in evaluating the potential effects of climate change and crop management strategies on various rice types and other crops.

In order to minimize the yield reduction, different adaptation techniques were investigated include altering the sowing date, altering the spacing, and planting alternative plant populations as the sowing time approaches. Changing the planting window affected the yield significantly. By planting five days earlier than the actual transplanting date, the negative effects of the temperature increase on rice yield are reduced. The simulated yield by preponing the planting by five days had increased the yields of 13.33 % in P1T1 treatment, 16.06 % in P1T2 treatment, 6.62 % in P2T1 treatment and 8.52 % in P2T2 treatment, comparing with its simulated yield with actual planting date. This shows that altering the planting dates has a significant impact on the rice production. Thus, it can be said that increasing rice output in the experimental area benefits from five days early sowings.

DSSAT Model results showed that, increase in particular, may make rice production more susceptible to transplanting dates in addition to decreasing yield (Basak et al., 2010; Hasan & Rahman, 2019; Jha et al., 2020). According to Azdawiya et al. (2016), Jha et al. 2020, and Alejo (2020), choosing the ideal planting windows can maximize output and save significant financial losses. Early rice planting will enhance rice yield by 3.4 % to 10.2 %, according to Zhang et al.'s (2023) simulation of the effect of modifying the planting date on rice yield using the DSSAT 4.5 for various experiments which are consistent with current findings as well. The planting of rice 10 days to 1 month early can be recognized as a non-cost climate change adaptation technique for rice production under various scenarios of increased temperatures, according to studies by Dharmarathna et al. (2012) and Lu et al. (2022b). The variation in the experimental results may be due to soil and weather parameters variation.

Temperature sensitivity, phenological changes, water availability, pest and disease dynamics, and the duration of the crop's growth cycle are all factors that can be influenced by the sowing date. An earlier sowing date may lead to accelerated growth stages, affecting the synchronization of flowering with optimal environmental conditions. Water availability may also be affected, especially in flooded regions. The timing of sowing can also affect the crop's growth cycle, potentially affecting grain filling and overall yield. Adapting sowing practices according to the locality and selecting suitable rice varieties are

crucial for maintaining or improving rice yield in the face of changing climate conditions. These findings could offer insightful information on the possible effects of climate change on rice yield as well as appropriate adaptive strategies to lessen the negative effects of future climate change in India and other rice-growing nations.

Changing the planting window affected the yield significantly. By planting five days earlier than the actual transplanting date, the negative effects of the temperature increase on rice yield are lessened. The simulated yield by preponing the planting by five days had increased the yields of 13.33 % in P1T1 treatment, 16.06 % in P1T2 treatment, 6.62 % in P2T1 treatment and 8.52 % in P2T2 treatment, comparing with its simulated yield with actual planting date. The yield rises in different simulated scenarios were also impotent and recommendable. Thus, it can be said that increasing rice output in the experimental area benefits from five days early sowings.

Therefore, we can conclude that the crop yield decreases with increasing temperature when analysing data from 2020 to 2100 under the SSP 5-8.5 scenario. This suggests that climate change is likely to lead to a decline in agricultural productivity, posing significant challenges for food security in the region. Therefore, it can be inferred that the projected impact of climate change on paddy yield in the Palakkad and Kozhikode district is consistent across all the five climate models considered under both the SSP245 and SSP585 scenarios. Adaptation strategies like changing the sowing date and nutrient management significantly reduce the predicted yield loss in the future climate scenarios.

Summary and Conclusions

6. Summary and Conclusions

Modern agriculture needs to improve more than ever because uncertainty surrounding climate change is a major issue. This chapter summarizes an in-depth examination of multiple facets, ranging from field experiments to the application of advanced models for assessing the dynamics of water and nutrient management under changing climatic scenarios. This study was focused to establish rice water and nutrient recommendations using various field experiments, calibration and validation of crop modelling using simulation studies, as well as to quantify the impact of various environmental variables including climatic and soil variability on rice growth and production under IPCC CMIP 6 – SSP climate changing scenarios, with the help of GIS and remote sensing tool. Additionally, studies were carried out to assess the effects of various postharvest management techniques on reducing methane emissions from rice fields. Through thoroughly examining each experiment, this thesis identified better management practices to give expected flexibility against changing climate situations and sustain the rice productivity. Seven distinct experiments that were meticulously conducted to meet the study's main objective are included in this thesis. Together, this research employed a range of strategies to address issues in water saving technologies, nutrient management, and other agronomic adaptation strategies in climate changing scenarios in rice farming.

- In conclusion, the first experiment evaluating different irrigation and nutrient management strategies on four rice varieties, namely Jyothi, Jaya, Uma, and Kanchana, revealed different treatments had significant impacts on plant biometric parameters. Throughout the three growth stages, measurements of plant height, number of tillers, Leaf Area Index (LAI), and number of panicles were recorded and it showed that, flooded conditions combined with 120 % nitrogen management exhibited superior growth characteristics. Least values were observed with Alternate Wetting and Drying (AWD) treatment applied with 0 % nitrogen. Among the varieties, Uma variety demonstrated significant responsiveness to the various treatments. Importantly, the experiment resulted in a substantial 37.52 % water savings compared to conventional flood irrigation, highlighting the potential for sustainable water management practices in rice cultivation. These findings highlight the importance of optimizing irrigation and nutrient management strategies for enhanced rice crop performance, with

implications for both productivity and resource conservation under changing climate scenario.

- Second experiment aimed at evaluating aerobic rice management techniques as a water-saving technology provided valuable insights into nutrient and planting strategies. Among the management approaches, Direct Seeding of Rice (DSR) with 125 % inorganic fertilizers exhibited superior yield and growth characteristics, emphasizing its potential for optimizing aerobic rice production. Conversely, transplanting with 100 % organic manure application resulted in least biometric parameters and resulting in poor yield , highlighting the importance of careful nutrient selection and method of planting for effective cultivation practices. Furthermore, the study made a noteworthy effort to quantify water savings achieved through aerobic rice cultivation across three growing seasons in Kerala. The findings emphasize the role of aerobic rice as a sustainable water-saving technology, with potential implications for water resource management in rice growing regions. As agriculture faces increasing challenges related to water scarcity, adopting such practices could contribute to both improved crop productivity and efficient utilization of water resources in rice farming.

- In the next phase, an experiment was conducted to evolve effective water and nutrient management practices under aerobic rice in lateritic soils in Kerala. Among the nutrient management strategies, the application of 125 % nitrogen in inorganic fertilizers significantly influenced plant growth and yield parameters, demonstrating its efficacy in enhancing rice productivity. On the other hand, the application of 75 % nitrogen showed the lowest impact. In the case of irrigation levels, even though the yield and other parameters are not statistically significant, but numerically higher values were observed in 120 % ET_C treatment. However, during the experiment with a few water stress treatments, rolling of leaves was observed, and when explored for the reasons, it was due to soil moisture deficit and plant water stress. Based on these results, a few experiments were conducted to understand the impact of leaf rolling on plant growth and physiological aspects. The results showed that plant growth parameters, relative water content (RWC), membrane leakage (ML), and spectral signatures were significantly affected by the leaf rolling, which resulted

in low productivity. A management strategy of adding cocopeat to the soil results in overcoming this water stress and also speedy recovery when water stress is induced. In addition, the novelty of using spectral signatures for identifying water stress was also explored, and it was found that the results were encouraging and with this advanced technology water stress in rice plants can be identified with the help of different vegetative indices. These findings confirm that for an aerobic rice production system, in midland lateritic soils of Kerala, to sustain the crop productivity of rice, the soil needs to be incorporated with cocopeat, which will help to retain the soil moisture sufficient for rice growth in the case of upland soils.

- Fourth experiment assessed the impact of various organic management practices on farmers' paddy yield, with the following treatments : P1 involved the application of basal nutrients using Farm Yard Manure (FYMs), P2 utilized compost along with basal nutrients, P3 incorporated Azolla with basal nutrients, P4 combination of both compost and Azolla with basal nutrients, and C represented the control plot with farmer's traditional management practices. The results demonstrated that the P4 treatment, which involved the joint application of compost and Azolla with basal nutrients, yielded not only enhanced growth characteristics but also exhibited superior crop yield . Moreover, to comprehend the fertility improvement under organic agriculture, a post-harvest soil analysis was conducted, and the results showed the positive impact of the organic management practices on soil health and nutrient levels. This assessed the potential benefits of incorporating compost and Azolla into basal nutrient applications for sustainable and improved paddy cultivation practices. Chemical fertilizers in farming improve plant nutrition but have long-term negative effects on soil, microorganisms, human health, and the environment and these organic farming practices will help in improving both soil and crop quality.

- In the fifth experiment assessing different post-harvest field management strategies to mitigate greenhouse gas (GHG) emissions at IRTA, Spain yielded valuable insights. Among the treatments tested, Non-Winter Flooding with Late Straw Incorporation (NWF LSI) demonstrated lower emissions compared to other treatments. The combination of non-winter flooding and delayed straw incorporation proved to be particularly effective in reducing GHG emissions.

Furthermore, the litter bag experiment corroborated these findings by indicating higher decomposition rates in flooded fields, supporting the link between flooding and methane emissions during the post-harvest period.

- The sixth experiment investigated the application of the crop simulation model, DSSAT to simulate the crop yield under different management practices, in terms of nutrients, water and planting methods, to identify the best management practices and also to understand the impact of weather parameters on rice growth. DSSAT-CERES Rice model was calibrated and validated for *Uma* rice cultivar with field experiment data. Rice yield simulated by the model under stress-free experiments closely matched with the field observed values indicated by low values of RMSE, MBE, MAPE and high correlation coefficient. Further, the model was used to project rice yield under temperature sensitivity analysis and predicted a decrease in rice production by an average of 37 % when the temperature increased by 1.5 ^{o}C in maximum and minimum temperature. The crop simulation model confirmed that with the increase in temperature, beyond a limit, rice yield tends to decline and hence suitable adaptation mechanism's needs to be evolved to sustain the rice production and for ensuring food security.
- In the final experiment, this study offers insightful information about how the Kozhikode and Palakkad districts' paddy farming is affected by climate change and potential solutions to reduce its adverse effects. Crop suitability analysis using the AHP method, revealed that most of the paddy land was highly or moderately suitable for both districts. These results can be considered as the solution for the identification of new cropping areas for upland rice cultivation in the climate change scenarios. The results of the study showed that climate change scenarios were likely to affect the paddy yield in the Palakkad district, as projected paddy yields decreased across all five climate models of IPCC CIMIP 6 considered (CMCC-ESM2, EC-Earth3, EC-Earth3-Veg, and GFDL-CM4) under both the SSP245 and SSP585 scenarios, with a corresponding increase in temperature. The combination of yield estimation, climatic scenario evaluation, and mapping of paddy adaptability can aid the identification of adaptation techniques. As an adaptation measure different sowing dates as well as altering the fertilizer management were attempted for future climate scenarios and the

results showed that yield reduction can be minimized by preponing the sowing date and applying more nitrogenous fertilizers.

Overall, the findings from this comprehensive study evaluated the critical impact of site-specific water and nutrient management practices on rice yield in the context of a changing climate. The field experiments emphasized the necessity of tailored approaches for optimizing yield, while crop modelling confirmed the upcoming threat of climate change-induced reductions in rice production, posing challenges to regional food security. Transitioning to water-efficient technologies, such as AWD/ Aerobic rice/ and precision farming with best management of nutrients, emerges as a viable solution, not only reducing the pressure on water resources but also enhancing overall agricultural efficiency. Moreover, the study highlights that the adoption of innovative water and nutrient management practices, integrated with Crop Simulation Models (CSM), holds promise for sustainable cultivation strategies. The sensitivity analysis with CSMs revealed strong relationships between rice growth and various factors, including weather, soil health, irrigation, planting methods, and rice varieties. In addition, effective post-harvest management practices which reduces the GHG emissions were also explored. As the region faces the challenges of climate change, the suitability study recommends identifying and utilizing every feasible space for paddy cultivation to address the growing demand for food. The results offer crucial insights for policymakers, farmers, and stakeholders, enabling them to make informed decisions and develop strategies to mitigate climate change's potential impacts on rice yield and overall agricultural productivity. By striking a balance between productivity and environmental stewardship, this research advocates for a more sustainable future in agriculture, contributing to the goal of a carbon-neutral state in Kerala by 2050 and securing the well-being of current and future generations

Recommendation and Future Perspective

7. Recommendation and Future Perspective

- Water and nutrient management practices significantly influenced the rice growth and yield - Direct Seeding of Rice (DSR) with 125% inorganic fertilizers exhibited superior yield and growth characteristics, emphasizing its potential for optimizing aerobic rice production.
- Alternate Wetting and Drying (AWD) technique can be implemented in up-land and mid-land area, wherever assured irrigation facilities are available, which results in water conservation and subsequent yield enhancement.
- Under aerobic rice cultivation, soil moisture must be closely monitored, and management strategies such as application of cocopeat and other moisture absorbent mediums needs to be used to sustain the crop and water productivity.
- Organic nutrient management practices with compost, Azolla and Farm yard manure resulted in higher paddy yield. Incorporation of organic amendments improves the water holding capacity, biotic stress and soil health.
- For low to medium N soils, a higher dose of N fertilizer is needed to increase yield. Soil tests should be conducted to determine the best recommendation.
- Site specific post-harvest straw management i.e. Non-Winter Flooding with Late Straw Incorporation reduces the GHG emissions from rice fields and hence this needs to be adopted in post-harvest flooded fields.
- Adjustment of crop calendar/ transplanting date/ Direct seeding date will reduce the negative impact of climate change and improve yield.

Future thrust

Results showed that different rice varieties exhibit distinct variations to the water and nutrient management practices in changing climatic scenario, hence leveraging advancements in genetics and biotechnology, rice varieties that can withstand the challenges posed by changing climates, including temperature extremes, altered precipitation patterns needs to be identified and given to the farmers for sustaining the rice production. Empowering farmers with the knowledge and skills are necessary to adapt to changing climates and hence policy should be designed in such a way to facilitate sustainable rice production in the face of evolving climatic conditions.

References

8. References

AbdelRahman, M. A., Natarajan, A., & Hegde, R. (2016). Assessment of land suitability and capability by integrating remote sensing and GIS for agriculture in Chamarajanagar district, Karnataka, India. *The Egyptian Journal of Remote Sensing and Space Science*, *19*(1), 125–141. https://doi.org/10.1016/j.ejrs.2016.02.001

Abdipour, M., Ebrahimi, M., Izadi-Darbandi, A., Mastrangelo, A. M., Najafian, G., Arshad, Y., & Mirniyam, G. (2016). Association between Grain Size and Shape and Quality Traits, and Path Analysis of Thousand Grain Weight in Iranian Bread Wheat Landraces from Different Geographic Regions. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, *44*(1). https://doi.org/10.15835/nbha.44.1.10256

Abimbola, O. P., Franz, T. E., Rudnick, D., Heeren, D., Yang, H., Wolf, A., Katimbo, A., Nakabuye, H. N., & Amori, A. (2022). Improving crop modeling to better simulate maize yield variability under different irrigation managements. *Agricultural Water Management*, *262*, 107429. https://doi.org/10.1016/j.agwat.2021.107429

Abou Hussien, E., Nada, W., & Mahrous, H. (2021). Improving Chemical and Microbial Properties of Calcareous Soil and its Productivity of Faba Bean (Vicia faba L.) Plants by using Compost Tea Enriched with Humic Acid and Azolla. *Egyptian Journal of Soil Science*, *0*(0), 0–0. https://doi.org/10.21608/ejss.2020.47611.1399

Adejuwon, J. O. (2005). Assessing the suitability of EPLIC Crop Model for use in the study of impacts of climate variability and climate change in West Africa. *Singapore Journal of Tropical Geography*, 24: 44-60. https://doi.org/10.1111/j.0129-7619.2005.00203x

Adiele, J., Schut, A., Ezui, K., & Giller, K. (2022). LINTUL-Cassava-NPK: A simulation model for nutrient-limited cassava growth. *Field Crops Research*, *281*, 108488. https://doi.org/10.1016/j.fcr.2022.108488

Agehara, S., & Warncke, D. D. (2005). Soil Moisture and Temperature Effects on Nitrogen Release from Organic Nitrogen Sources. *Soil Science Society of America Journal*, *69*(6), 1844–1855. https://doi.org/10.2136/sssaj2004.0361

Aggarwal, P., Banerjee, B., Daryaei, M., Bhatia, A., Bala, A., Rani, S., Chander, S., Pathak, H., & Kalra, N. (2006a). InfoCrop: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. II. Performance of the model. *Agricultural Systems*, *89*(1), 47–67. https://doi.org/10.1016/j.agsy.2005.08.003

Aggarwal, P., Kalra, N., Chander, S., & Pathak, H. (2006b). InfoCrop: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. I. Model description. *Agricultural Systems*, *89*(1), 1–25. https://doi.org/10.1016/j.agsy.2005.08.001

Aggarwal, P., Kropff, M., Cassman, K., & ten Berge, H. (1997). Simulating genotypic strategies for increasing rice yield potential in irrigated, tropical environments. *Field Crops Research*, *51*(1–2), 5–17. https://doi.org/10.1016/s0378-4290(96)01044-1

Ahamed, T., Tian, L., Zhang, Y., & Ting, K. (2011). A review of remote sensing methods for biomass feedstock production. *Biomass and Bioenergy*, *35*(7), 2455–2469. https://doi.org/10.1016/j.biombioe.2011.02.028

Ahmad, A., Ali, A., Khaliq, T., Wajid, S. A., Iqbal, Z., Ibrahim, M., Rashad Javeed, H. M., & Hoogenboom, G. (2013a). OILCROP-SUN Model Relevance for Evaluation of Nitrogen Management of Sunflower Hybrids in Sargodha, Punjab. *American Journal of Plant Sciences*, *04*(09), 1731–1735. https://doi.org/10.4236/ajps.2013.49212

Ahmad, I., Saeed, U., Fahad, M., Ullah, A., Habib ur Rahman, M., Ahmad, A., & Judge, J. (2018). Yield Forecasting of Spring Maize Using Remote Sensing and Crop Modeling in Faisalabad-Punjab Pakistan. *Journal of the Indian Society of Remote Sensing*, *46*(10), 1701–1711. https://doi.org/10.1007/s12524-018-0825-8

Ahmad, L., & Mahdi, S. S. (2019). *Satellite Farming*. Springer. http://books.google.ie/books?id=WFWIDwAAQBAJ&printsec=frontcover&dq=Satellite+Farming+An+Information+and+Technology+Based+Agriculture&hl=&cd=1&source=gbs_api

Ahmad, S., Ahmad, A., Ali, H., Hussain, A., Garcia y Garcia, A., Khan, M. A., Zia-Ul-Haq, M., Hasanuzzaman, M., & Hoogenboom, G. (2013b). Application of the CSM-CERES-Rice model for evaluation of plant density and irrigation management of transplanted rice for an irrigated semiarid environment. *Irrigation Science*, *31*(3), 491–506. https://doi.org/10.1007/s00271-012-0324-6

Ahmad, S., Ahmad, A., Soler, C. M. T., Ali, H., Zia-Ul-Haq, M., Anothai, J., Hussain, A., Hoogenboom, G., & Hasanuzzaman, M. (2011). Application of the CSM-CERES-Rice model for evaluation of plant density and nitrogen management of fine transplanted rice for an irrigated semiarid environment. *Precision Agriculture*, *13*(2), 200–218. https://doi.org/10.1007/s11119-011-9238-1

Ajith, K., Geethalakshmi, V., Ragunath, K., Pazhanivelan, S., & Panneerselvam, S. (2017, July 10). Rice Acreage Estimation in Thanjavur, Tamil Nadu Using Lands at 8 OLIIMAGES and GIS Techniques. International Journal of Current Microbiology and Applied Sciences, 6(7), 2327–2335. https://doi.org/10.20546/ijcmas.2017.607.275

Akhgari, H., & Kaviani, B. (2011). Assessment of direct seeded and transplanting methods of rice cultivars in the northern part of Iran. *African Journal Of Agricultural Reseearch*, *6*(31). https://doi.org/10.5897/ajar11.973

Akhtar, M., Sarwar, N., Ashraf, A., Ejaz, A., Ali, S., & Rizwan, M. (2020). Beneficial role of Azolla sp. in paddy soils and their use as bioremediators in polluted aqueous environments: implications and future perspectives. *Archives of Agronomy and Soil Science*, *67*(9), 1242–1255. https://doi.org/10.1080/03650340.2020.1786885

Akinbile, C. O., Ogundipe, A., & Davids, R. O. (2020). Crop water requirements, biomass and grain yields estimation for upland rice using CROPWAT, AQUACROP and CERES simulation models. *Agricultural Engineering International: CIGR Journal*, *22*(2), 1-20.

Akondo, M. R. I., Hossain, M. B., Akter, S. E., & Islam, M. M. (2020). Comparative Performance of System of Rice Intensification (SRI) and Conventional Methods of Rice Cultivation in Gopalganj District of Bangladesh. *Asian Plant Research Journal*, 1–7. https://doi.org/10.9734/aprj/2020/v6i430133

Alauddin, M., Rashid Sarker, M. A., Islam, Z., & Tisdell, C. (2020). Adoption of alternate wetting and drying (AWD) irrigation as a water-saving technology in Bangladesh: Economic and environmental considerations. *Land Use Policy*, *91*, 104430. https://doi.org/10.1016/j.landusepol.2019.104430

Alejo, L. A. (2020). Assessing the impacts of climate change on aerobic rice production using the DSSAT-CERES-Rice model. *Journal of Water and Climate Change*, *12*(3), 696–708. https://doi.org/10.2166/wcc.2020.286

Al-Hanbali, A., Shibuta, K., Alsaaideh, B., & Tawara, Y. (2021). Analysis of the land suitability for paddy fields in Tanzania using a GIS-based analytical hierarchy process. *Geo-Spatial Information Science*, *25*(2), 212–228. https://doi.org/10.1080/10095020.2021.2004079

Ali, A., Erenstein, O., & Rahut, D. B. (2014). Impact of direct rice-sowing technology on rice producers' earnings: empirical evidence from Pakistan. *Development Studies Research*, *1*(1), 244–254. https://doi.org/10.1080/21665095.2014.943777

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome*, *300*(9), D05109.

Alley, M. M., Scharf, P. C., Brann, D. E., Baethgen, W. E., & Hammons, J. L. (2009). Nitrogen management for winter wheat: principles and recommendations.

Altor, A. E., & Mitsch, W. J. (2008). Pulsing hydrology, methane emissions and carbon dioxide fluxes in created marshes: A 2-year ecosystem study. *Wetlands*, *28*(2), 423–438. https://doi.org/10.1672/07-98.1

Amiri, E., Rezaei, M., Bannayan, M., & Soufizadeh, S. (2013). Calibration and Evaluation of CERES Rice Model under Different Nitrogen- and Water-Management Options in Semi-Mediterranean Climate Condition. *Communications in Soil Science and Plant Analysis*, *44*(12), 1814–1830. https://doi.org/10.1080/00103624.2013.769565

Andrews, E. M., Kassama, S., Smith, E. E., Brown, P. H., & Khalsa, S. D. S. (2021). A Review of Potassium-Rich Crop Residues Used as Organic Matter Amendments in Tree Crop Agroecosystems. *Agriculture*, *11*(7), 580. https://doi.org/10.3390/agriculture11070580

Anothai, J., Soler, C., Green, A., Trout, T., & Hoogenboom, G. (2013). Evaluation of two evapotranspiration approaches simulated with the CSM–CERES–Maize model under different irrigation strategies and the impact on maize growth, development and soil moisture content for semi-arid conditions. *Agricultural and Forest Meteorology*, *176*, 64–76. https://doi.org/10.1016/j.agrformet.2013.03.001

Ansari, T. H., Yamamoto, Y., Yoshida, T., Miyazaki, A., & Wang, Y. (2003). Cultivar differences in the number of differentiated spikelets and percentage of degenerated spikelets as determinants of the spikelet number per panicle in relation to dry matter production and nitrogen absorption. *Soil Science and Plant Nutrition*, *49*(3), 433–444. https://doi.org/10.1080/00380768.2003.10410029

Anupoju, V., & Kambhammettu, B. V. N. P. (2020). Role of deficit irrigation strategies on ET partition and crop water productivity of rice in semi-arid tropics of south India. *Irrigation Science*, *38*(4), 415–430. https://doi.org/10.1007/s00271-020-00684-1

Araya, A., Prasad, P., Ciampitti, I., & Jha, P. (2021). Using crop simulation model to evaluate influence of water management practices and multiple cropping systems on crop yields: A case study for Ethiopian highlands. *Field Crops Research*, *260*, 108004. https://doi.org/10.1016/j.fcr.2020.108004

Arvidsson, J., & Håkansson, I. (1991). A model for estimating crop yield losses caused by soil compaction. *Soil and Tillage Research*, *20*(2–4), 319–332. https://doi.org/10.1016/0167-1987(91)90046-z

Asadi, M., Nasiri, Y., Maggi, F., Rasouli, F., & Morshedloo, M. R. (2023). Biomass Yield and Essential Oil Chemical Composition of Mentha x piperita as Affected by Amino Acids and Different Fertilizer Resources. *Journal of Soil Science and Plant Nutrition*, *23*(1), 668–682. https://doi.org/10.1007/s42729-022-01073-7

Aswathi K. P., Ajith K., Ajithkumar B., & Abida P. S. (2022). Impact of climate change on rice yield under projected scenarios in central zone of Kerala. *Journal of Agrometeorology*, *24*(3). https://doi.org/10.54386/jam.v24i3.1544

Aulakh, M. S., & Malhi, S. S. (2005). Interactions of nitrogen with other nutrients and water: Effect on crop yield and quality, nutrient use efficiency, carbon sequestration, and environmental pollution. *Advances in agronomy*, *86*, 341-409.

Awang, Y., Shaharom, A. S., Mohamad, R. B., & Selamat, A. (2009). Chemical and Physical Characteristics of Cocopeat-Based Media Mixtures and Their Effects on the Growth and Development of *Celosia cristata*. *American Journal of Agricultural and Biological Sciences*, *4*(1), 63–71. https://doi.org/10.3844/ajabssp.2009.63.71

Ayehu, G., Tadesse, T., Gessesse, B., & Yigrem, Y. (2019). Soil Moisture Monitoring Using Remote Sensing Data and a Stepwise-Cluster Prediction Model: The Case of Upper Blue Nile Basin, Ethiopia. *Remote Sensing*, *11*(2), 125. https://doi.org/10.3390/rs11020125

Azdawiyah, A. T., Zabawi, A. M., Hariz, A. M., Fairuz, M. M., Fauzi, J., & Faisal, M. M. S. (2016). Simulating Climate Change Impact on Rice Yield in Malaysia Using DSSAT 4.5: Shifting Planting Date as an Adaptation Strategy. *NIAES Ser*, *6*, 115-125.

Azmal, A. K. M., Marumoto, T., Shindo, H., & Nishiyama, M. (1997). Changes in microbial biomass after continuous application of azolla and rice straw in soil. *Soil Science and Plant Nutrition*, *43*(4), 811–818. https://doi.org/10.1080/00380768.1997.10414647

Badshah, M., Naimei, T., Zou, Y., Ibrahim, M., & Wang, K. (2014). Yield and tillering response of super hybrid rice Liangyoupeijiu to tillage and establishment methods. *The Crop Journal*, *2*(1), 79–86. https://doi.org/10.1016/j.cj.2013.11.004

Bahmaniar, M., & Ranjbar, G. (2007). Response of Rice Cultivars to Rates of Nitrogen and Potassium Application in Field and Pot Conditions. *Pakistan Journal of Biological Sciences*, *10*(9), 1430–1437. https://doi.org/10.3923/pjbs.2007.1430.1437

Bakhsh, I., Awan, I., Sadiq, M., Niamatullah, M., Zaman, K. U., & Aftab, M. (2011). Effect of plant growth regulator application at different growth stages on the economical yield

potential of coarse rice (Oryza sativa L.). *JAPS, Journal of Animal and Plant Sciences*, *21*(3), 612-616.

Bannayan, M., Crout, N. M. J., & Hoogenboom, G. (2003). Application of the CERES-Wheat Model for Within-Season Prediction of Winter Wheat Yield in the United Kingdom. *Agronomy Journal*, *95*(1), 114–125. https://doi.org/10.2134/agronj2003.1140a

Bao, Y., Hoogenboom, G., McClendon, R., & Vellidis, G. (2017). A comparison of the performance of the CSM-CERES-Maize and EPIC models using maize variety trial data. *Agricultural Systems*, *150*, 109–119. https://doi.org/10.1016/j.agsy.2016.10.006

Barati, S., Rayegani, B., Saati, M., Sharifi, A., & Nasri, M. (2011). Comparison the accuracies of different spectral indices for estimation of vegetation cover fraction in sparse vegetated areas. *The Egyptian Journal of Remote Sensing and Space Science*, *14*(1), 49-56.

Basak, J. K., Ali, M. A., Islam, M. N., & Rashid, M. A. (2010). Assessment of the effect of climate change on boro rice production in Bangladesh using DSSAT model. *Journal of Civil Engineering (IEB)*, *38*(2), 95-108.

Basso, B., & Ritchie, J. T. (2015). Simulating crop growth and biogeochemical fluxes in response to land management using the SALUS model (Vol. 2015, pp. 252-274). Oxford: Oxford University Press.

Batchelor, W. D., Jones, J. W., Boote, K. J., & Pinnschmidt, H. O. (1993). Extending the use of crop models to study pest damage. *Transactions of the ASAE*, *36*(2), 551-558.

Beadle, C. L. (1987). Plant growth analysis. In: Coombs J, Hall D O, Long S P, Scurlock J M O, eds., Techniques in Bio Productivity and Photosynthesis. 2nd ed. Pergamon Press, Oxford, New York. pp. 21–23

Belenguer-Manzanedo, M., Alcaraz, C., Camacho, A., Ibáñez, C., Català-Forner, M., & Martínez-Eixarch, M. (2022). Effect of post-harvest practices on greenhouse gas emissions in rice paddies: flooding regime and straw management. *Plant and Soil*, *474*(1–2), 77–98. https://doi.org/10.1007/s11104-021-05234-y

Bemal, S., Singh, D., & Singh, S. (2013). Impact analysis of climate variability on rice productivity in eastern agroclimatic zone of Haryana by using DSSAT crop model. *J. Agrometeorol*, *15*, 80-84.

Benbi, D. K., & Khosa, M. K. (2014). Effects of Temperature, Moisture, and Chemical Composition of Organic Substrates on C Mineralization in Soils. *Communications in Soil Science and Plant Analysis*, *45*(21), 2734–2753. https://doi.org/10.1080/ 00103624. 2014.950423

Bergez, J., Raynal, H., Launay, M., Beaudoin, N., Casellas, E., Caubel, J., Chabrier, P., Coucheney, E., Dury, J., Garcia de Cortazar-Atauri, I., Justes, E., Mary, B., Ripoche, D., & Ruget, F. (2014). Evolution of the STICS crop model to tackle new environmental issues: New formalisms and integration in the modelling and simulation platform RECORD. *Environmental Modelling & Software*, *62*, 370–384. https://doi.org/10.1016/ j.envsoft. 2014.07.010

Bhatt, R., Kaur, R., & Ghosh, A. (2019). Strategies to practice climate-smart agriculture to improve the livelihoods under the rice-wheat cropping system in South Asia. In *Sustainable Management of Soil and Environment* (pp. 29-71). Springer, Singapore.

Bhattacharya, A. (2018). *Changing climate and resource use efficiency in plants*. Academic Press.

Bhattacharyya, P. N., Goswami, M. P., & Bhattacharyya, L. H. (2016). Perspective of beneficial microbes in agriculture under changing climatic scenario: a review. *Journal of Phytology*, *8*, 26. https://doi.org/10.19071/jp.2016.v8.3022

Bhuvaneswari, K., Geethalakshmi, V., Lakshmanan, A., Anbhazhagan, R., & Sekhar, D. N. U. (2014). Climate change impact assessment and developing adaptation strategies for rice crop in western zone of Tamil Nadu. *Journal of Agrometeorology*, *16*(1), 38-43.

Blokhina, O., Virolainen, E., & Fagerstedt, K. V. (2003). Antioxidants, Oxidative Damage and Oxygen Deprivation Stress: a Review. *Annals of Botany*, *91*(2), 179–194. https://doi.org/10.1093/aob/mcf118

Boegh, E., Soegaard, H., Broge, N., Hasager, C., Jensen, N., Schelde, K., & Thomsen, A. (2002). Airborne multispectral data for quantifying leaf area index, nitrogen concentration, and

photosynthetic efficiency in agriculture. *Remote Sensing of Environment*, *81*(2–3), 179–193. https://doi.org/10.1016/s0034-4257(01)00342-x

Boggess, W. G., & Amerling, C. B. (1983). A Bioeconomic Simulation Analysis of Irrigation Investments. *Journal of Agricultural and Applied Economics*, *15*(2), 85–91. https://doi.org/10.1017/s0081305200016290

Boomsma, C. R., Santini, J. B., West, T. D., Brewer, J. C., McIntyre, L. M., & Vyn, T. J. (2010). Maize grain yield responses to plant height variability resulting from crop rotation and tillage system in a long-term experiment. *Soil and Tillage Research*, *106*(2), 227–240. https://doi.org/10.1016/j.still.2009.12.006

Boote, K. J., Allen Jr, L. H., Prasad, P. V., & Jones, J. W. (2010). Testing effects of climate change in crop models. *Handbook of climate change and agroecosystems. Imperial College Press, London*, 109-129.

Borus, D., Parsons, D., Boersma, M., Brown, H., & Mohammed, C. (2018). Improving the prediction of potato productivity: APSIM-Potato model parameterization and evaluation in Tasmania, Australia. *Australian Journal of Crop Science*, *12*(1), 32–43. https://doi.org/10.21475/ajcs.18.12.01.pne570

Bouman, B. A., Humphreys, E., Tuong, T. P., & Barker, R. (2007). Rice and water. *Advances in agronomy*, *92*, 187-237.

Bouman, B., & van Laar, H. (2006). Description and evaluation of the rice growth model ORYZA2000 under nitrogen-limited conditions. *Agricultural Systems*, *87*(3), 249–273. https://doi.org/10.1016/j.agsy.2004.09.011

Bouman, B., van Keulen, H., van Laar, H., & Rabbinge, R. (1996). The 'School of de Wit' crop growth simulation models: A pedigree and historical overview. *Agricultural Systems*, *52*(2–3), 171–198. https://doi.org/10.1016/0308-521x(96)00011-x

Bowen, W. T., Lal, S. S., & Govindakrishnan, P. M. (2002). Simulation of potato-based cropping systems. In *Potato, global research & development. Proceedings of the Global Conference on Potato, New Delhi, India, 6-11 December, 1999: Volume 2* (pp. 776-787). Indian Potato Association.

Boylan, J. W., & Russell, A. G. (2006). PM and light extinction model performance metrics, goals, and criteria for three-dimensional air quality models. *Atmospheric Environment*, *40*(26), 4946–4959. https://doi.org/10.1016/j.atmosenv.2005.09.087

Bray, r. H., & kurtz, l. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science*, *59*(1), 39–46. https://doi.org/10.1097/00010694-194501000-00006

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussière, F., Cabidoche, Y., Cellier, P., Debaeke, P., Gaudillère, J., Hénault, C., Maraux, F., Seguin, B., & Sinoquet, H. (2003). An overview of the crop model stics. *European Journal of Agronomy*, *18*(3–4), 309–332. https://doi.org/10.1016/s1161-0301(02)00110-7

Buresh, R. J., Correa, T. Q., Pabuayon, I. L. B., Laureles, E. V., & Choi, I. R. (2021). Yield of irrigated rice affected by asymptomatic disease in a long-term intensive monocropping experiment. *Field Crops Research*, *265*, 108121. https://doi.org/10.1016/ j.fcr. 2021. 108121

Busato, P. (2015). A simulation model for a rice-harvesting chain. *Biosystems Engineering*, *129*, 149–159. https://doi.org/10.1016/j.biosystemseng.2014.09.012

Cabangon, R. J., Castillo, E. G., Bao, L. X., Lu, G., Wang, G. H., Cui, Y. L., Toung, T. P.,Bouman, B. A. M., Li, Y. H., Chen, C. D., & Wang, J. Z. (2001). Impact of alternate wetting and drying irrigation on rice growth and resource-use efficiency. *Barker R, Loeve R, Li YH, Tuong TP, editors*, 55-80.

Cahn, M., & Johnson, L. (2017, April 18). New Approaches to Irrigation Scheduling of Vegetables. *Horticulturae*, *3*(2), 28. https://doi.org/10.3390/horticulturae3020028

Camacho, A., Picazo, A., Rochera, C., Santamans, A., Morant, D., Miralles-Lorenzo, J., & Castillo-Escrivà, A. (2017). Methane Emissions in Spanish Saline Lakes: Current Rates, Temperature and Salinity Responses, and Evolution under Different Climate Change Scenarios. *Water*, *9*(9), 659. https://doi.org/10.3390/w9090659

Cammarano, D., Payero, J., Basso, B., Wilkens, P., & Grace, P. (2012). Agronomic and economic evaluation of irrigation strategies on cotton lint yield in Australia. *Crop and Pasture Science*, *63*(7), 647. https://doi.org/10.1071/cp12024

Cao, X., Zhong, C., Sajid, H., Zhu, L., Zhang, J., Wu, L., & Jin, Q. (2017). Effects of watering regime and nitrogen application rate on the photosynthetic parameters, physiological characteristics, and agronomic traits of rice. *Acta Physiologiae Plantarum*, *39*(6). https://doi.org/10.1007/s11738-017-2432-7

Car, N. J., Christen, E. W., Hornbuckle, J. W., & Moore, G. A. (2012). Using a mobile phone Short Messaging Service (SMS) for irrigation scheduling in Australia – Farmers' participation and utility evaluation. *Computers and Electronics in Agriculture*, *84*, 132–143. https://doi.org/10.1016/j.compag.2012.03.003

Carlson, K. M., Gerber, J. S., Mueller, N. D., Herrero, M., MacDonald, G. K., Brauman, K. A., Havlik, P., O'Connell, C. S., Johnson, J. A., Saatchi, S., & West, P. C. (2016). Greenhouse gas emissions intensity of global croplands. *Nature Climate Change*, *7*(1), 63–68. https://doi.org/10.1038/nclimate3158

Carrijo, D. R., Lundy, M. E., & Linquist, B. A. (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crops Research*, *203*, 173–180. https://doi.org/10.1016/j.fcr.2016.12.002

Casadesús, J., Mata, M., Marsal, J., & Girona, J. (2012). A general algorithm for automated scheduling of drip irrigation in tree crops. *Computers and Electronics in Agriculture*, *83*, 11–20. https://doi.org/10.1016/j.compag.2012.01.005

Chadhar, A. R., Nadeem, M. A., Ali, H. H., Safdar, M. E., Raza, A., Adnan, M., Hussain, M., Ali, L.& Javaid, M. M. (2020). Quantifying the impact of plant spacing and critical weed competition period on fine rice production under the system of rice intensification. *Int. J. Agri. Biol*, *24*(5), 1142-1148. . https://doi.org/10.17957/IJAB/15.1543

Chakraborty, D., Ladha, J. K., Rana, D. S., Jat, M. L., Gathala, M. K., Yadav, S., Rao, A. N., Ramesha, M. S., & Raman, A. (2017). A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-09742-9

Chandana, V. M., Singh, M. K., & Kumar, A. (2019). Water saving technologies in rice-a review. *Journal of Pharmacognosy and Phytochemistry*, *8*(5), 2516-2523.

Chandra, K., Prasad, Y., Haider, Z. A., Kumar, R., & Kumar, K. (2008). Quantitative analysis of upland rice. *ORYZA-An International Journal on Rice*, *45*(4), 268-272.

Chandrakala, M., Srinivasan, R., `Kumar, K. S. A., Sujatha, K., Hegde, R., Singh, S. K., & Nirmala, H. R. (2019). Land Suitability Evaluation for Rubber in the Tropical Humid Region of Kerala, India. *Current Journal of Applied Science and Technology*, 1–9. https://doi.org/10.9734/cjast/2019/v35i530199

Chapman, S. C., Hammer, G. L., & Meinke, H. (1993). A Sunflower Simulation Model: I. Model Development. *Agronomy Journal*, *85*(3), 725–735. https://doi.org/10.2134/ agronj1993. 00021962008500030038x

Chaturvedi, A. K., Surendran, U., Gopinath, G., Chandran, K. M., NK, A., & CT, M. F. (2019). Elucidation of stage specific physiological sensitivity of okra to drought stress through leaf gas exchange, spectral indices, growth and yield parameters. *Agricultural Water Management*, *222*, 92–104. https://doi.org/10.1016/j.agwat.2019.05.041

Chaturvedi, G. S., Singh, A., & Bahadur, R. (2012). Screening techniques for evaluating crop germplasm for drought tolerance. *Plant Archives*, *12*(1), 11-18.

Chaudhari, N., Kumar, N., Parmar, P., Dakhore, K., Chaudhari, S., & Chandrawanshi, S. (2019). Assessment of Impact of Temperature and CO2 on Growth and yield of Rice Crop using DSSAT Model. *International Journal of Current Microbiology and Applied Sciences*, *8*(02), 776–783. https://doi.org/10.20546/ijcmas.2019.802.089

Chauhan, J. S., Chauhan, V. S., & Variar, M. (1993). Genetic variation and character association in rainfed upland rice. *Oryza*, *30*, 116-116.

Chaurasiya, G., Saxena, S., Tripathy, R., Chaudhari, K. N., & Ray, S. S. (2017). Semi physical approach for sugarcane yield modelling with remotely sensed inputs. *Vayu Mandal*, *43*(1), 11-22.

Cheeroo-Nayamuth, F., Robertson, M., Wegener, M., & Nayamuth, A. (2000). Using a simulation model to assess potential and attainable sugar cane yield in Mauritius. *Field Crops Research*, *66*(3), 225–243. https://doi.org/10.1016/s0378-4290(00)00069-1

Chen, C., Wang, E., & Yu, Q. (2010). Modelling the effects of climate variability and water management on crop water productivity and water balance in the North China Plain. *Agricultural Water Management*, *97*(8), 1175–1184. https://doi.org/10.1016/ j.agwat. 2008.11.012

Cheng, H., Shu, K., Zhu, T., Wang, L., Liu, X., Cai, W., Qi, Z., & Feng, S. (2022). Effects of alternate wetting and drying irrigation on yield, water and nitrogen use, and greenhouse gas emissions in rice paddy fields. *Journal of Cleaner Production*, *349*, 131487. https://doi.org/10.1016/j.jclepro.2022.131487

Chirayath, L. D. (1988). *Forms of water loss and water requirement of rice in kole lands* (Doctoral dissertation, Department of Land and Water Resources and Conservation Engineering, Kelappaji College of Agricultural Engineering and Technology, Tavanur).

Choruma, D. J., Balkovic, J., & Odume, O. N. (2019). Calibration and Validation of the EPIC Model for Maize Production in the Eastern Cape, South Africa. *Agronomy*, *9*(9), 494. https://doi.org/10.3390/agronomy9090494

Choudhary, A. K. (2003). Studies on chemical fertilizers economy and yield sustainability through IPNS in rice wheat cropping system.

Ciampitti, I. A., & Vyn, T. J. (2011). A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. *Field Crops Research*, *121*(1), 2–18. https://doi.org/10.1016/j.fcr.2010.10.009

Clerget, B., Bueno, C., Domingo, A. J., Layaoen, H. L., & Vial, L. (2016). Leaf emergence, tillering, plant growth, and yield in response to plant density in a high-yielding aerobic rice crop. *Field Crops Research*, *199*, 52–64. https://doi.org/10.1016/j.fcr.2016.09.018

Confalonieri, R., & Bocchi, S. (2005). Evaluation of CropSyst for simulating the yield of flooded rice in northern Italy. *European Journal of Agronomy*, *23*(4), 315–326. https://doi.org/ 10.1016/j.eja.2004.12.002

Confalonieri, R., Rosenmund, A. S., & Baruth, B. (2009). An improved model to simulate rice yield. *Agronomy for Sustainable Development*, *29*(3), 463–474. https://doi.org/ 10.1051/ agro/2009005

Conway, G. (2019). *The doubly green revolution: food for all in the twenty-first century*. Cornell University Press.

Corbeels, M., Berre, D., Rusinamhodzi, L., & Lopez-Ridaura, S. (2018). Can we use crop modelling for identifying climate change adaptation options? *Agricultural and Forest Meteorology*, *256–257*, 46–52. https://doi.org/10.1016/j.agrformet.2018.02.026

Craswell, E. T., & Vlek, P. L. G. (1982). Nitrogen management for submerged rice soils. In *Proceedings 12th International Congress of Soil Science, New Delhi* (Vol. 3, pp. 158-181).

Crippen, R. (1990, October). Calculating the vegetation index faster. *Remote Sensing of Environment*, *34*(1), 71–73. https://doi.org/10.1016/0034-4257(90)90085-z

Darikandeh, D., Shahnazari, A., Khoshravesh, M., & Hoogenboom, G. (2023). Correction to: Evaluating rice yield and adaptation strategies under climate change based on the CSM-CERES-Rice model: a case study for northern Iran. *Theoretical and Applied Climatology*, 151(3–4), 987–987. https://doi.org/10.1007/s00704-023-04359-7

Das, A., Layek, J., Ramkrushna, G. I., Patel, D. P., Choudhury, B. U., Krishnappa, R., Buragohain, J., & Yadav, G. S. (2017). Modified system of rice intensification for higher crop and water productivity in Meghalaya, India: opportunities for improving livelihoods for resource-poor farmers. *Paddy and Water Environment*, 16(1), 23–34. https://doi. org/ 10.1007/s10333-017-0609-8

Dash, J. C., Sarangi, A., Singh, D. K., Singh, A. K., & Adhikary, P. P. (2014). Prediction of root zone water and nitrogen balance in an irrigated rice field using a simulation model. *Paddy and Water Environment*, *13*(3), 281–290. https://doi.org/10.1007/s10333-014-0439-x

Dass, A., Suri, V. K., & Choudhary, A. K. (2014). Site-specific nutrient management approaches for enhanced nutrient-use efficiency in agricultural crops. *Research and Reviews: Journal of Crop Science and Technology*, *3*(3), 1-6.

Davies, W. P. (2003). An Historical Perspective from the Green Revolution to the Gene Revolution. *Nutrition Reviews*, *61*(suppl_6), S124–S134. https://doi.org/10.1301/ nr.2003. jun.s124-s134

de Borja Reis, F. A., Estevam Munhoz de Almeida, R., Cocco Lago, B., Trivelin, P. C., Linquist, B., & Favarin, J. L. (2018). Aerobic rice system improves water productivity, nitrogen recovery and crop performance in Brazilian weathered lowland soil. *Field Crops Research*, *218*, 59–68. https://doi.org/10.1016/j.fcr.2018.01.002

De Wit, C. T. (1965). *Photosynthesis of Leaf Canopies*. http://books. google.ie/ books?id= pEyAaqS9xaEC&q=Photosynthesis+of+leaf+canopies&dq=Photosynthesis+of+leaf+canopies&hl=&cd=2&source=gbs_api

Delgado, B., Paredes, M., & Martínez, M. (2015). Software application for calculating solar radiation and equivalent evaporation in mobile devices. *Agricultural Water Management*, *151*, 30–36. https://doi.org/10.1016/j.agwat.2014.09.012

Deosarkar, D. B., Misal, M. B., & Nerkar, Y. S. (1989). Variability and correlation studies for yield and yield contributing characters in breeding lines of upland rice. *Journal of Maharashtra Agricultural Univ*ersity *14*(1), 28-29.

Devêvre, O. C., & Horwáth, W. R. (2000). Decomposition of rice straw and microbial carbon use efficiency under different soil temperatures and moistures. *Soil Biology and Biochemistry*, *32*(11–12), 1773–1785. https://doi.org/10.1016/s0038-0717(00)00096-1

Devika, R., Bai, N. R., & Kumary, S. L. (2006). 'Uma'(MO 16) and 'Revathy'(MO 17): Two promising rice varieties with seed dormancy. *Journal of Tropical Agriculture*, *42*, 13-16.

Dharmarathna, W. R. S. S., Herath, S., & Weerakoon, S. B. (2012). Changing the planting date as a climate change adaptation strategy for rice production in Kurunegala district, Sri Lanka. *Sustainability Science*, *9*(1), 103–111. https://doi.org/10.1007/s11625-012-0192-2

Dhinesh, K., Radhakrishnan, S., Balasubramanian, A., & Sivakumar, K. (2019). Comparative Study of Soil Nutrient Status in Three Forest Types of Dharmapuri Forest Circle, Tamil Nadu, South India. *International Journal of Current Microbiology and Applied Sciences*, *8*(02), 1613–1621. https://doi.org/10.20546/ijcmas.2019.802.189

Diacono, M., & Montemurro, F. (2010). Long-term effects of organic amendments on soil fertility. A review. *Agronomy for Sustainable Development*, *30*(2), 401–422. https://doi.org/ 10. 1051/ agro/2009040

Dias, M., Navaratne, C., Weerasinghe, K., & Hettiarachchi, R. (2016). Application of DSSAT Crop Simulation Model to Identify the Changes of Rice Growth and Yield in Nilwala River Basin for Mid-centuries under Changing Climatic Conditions. *Procedia Food Science*, *6*, 159–163. https://doi.org/10.1016/j.profoo.2016.02.039

Ding, C., You, J., Chen, L., Wang, S., & Ding, Y. (2013). Nitrogen fertilizer increases spikelet number per panicle by enhancing cytokinin synthesis in rice. *Plant Cell Reports*, *33*(2), 363–371. https://doi.org/10.1007/s00299-013-1536-9

Ding, Y., Wang, W., ZD, Q., & Luo, Y. (2020). Adaptation of paddy rice in China to climate change: The effects of shifting sowing date on yield and irrigation water requirement. *Agricultural Water Management*, *228*, 105890. https://doi.org/10.1016/ j.agwat. 2019. 105890

Dingkuhn, M., Schnier, H., Datta, S., Wijangco, E., & Dorffling, K. (1990). Diurnal and Developmental Changes in Canopy Gas Exchange in Relation to Growth in Transplanted and Direct-Seeded Flooded Rice. *Functional Plant Biology*, *17*(2), 119. https://doi.org/10.1071/pp9900119

Divya, K. L., Mhatre, P. H., Venkatasalam, E. P., & Sudha, R. (2020). Crop Simulation Models as Decision-Supporting Tools for Sustainable Potato Production: a Review. *Potato Research*, *64*(3), 387–419. https://doi.org/10.1007/s11540-020-09483-9

DoES, (2023). Department of Econommics and Statistics, Kerala.

Dong, B., Molden, D., Loeve, R., Li, Y. H., Chen, C. D., & Wang, J. Z. (2004). Farm level practices and water productivity in Zhanghe Irrigation System. *Paddy and Water Environment*, *2*(4), 217–226. https://doi.org/10.1007/s10333-004-0066-z

Dong, X., Qi, D., Chen, B., Wu, Y., Zheng, X., & Lin, H. (2024). Differential roles of anthropogenic CO_2 in mediating seasonal amplitudes of ocean acidification metrics over a coastal coral habitat. *Journal of Marine Systems*, *241*, 103910. https://doi.org/10.1016/j.jmarsys.2023.103910

Doorenbos, J., & Kassam, A. H. (1979). Yield response to water. *Irrigation and drainage paper*, *33*, 257.

Duc, T. T. (2006). Using GIS and AHP technique for land-use suitability analysis. In *International symposium on geoinformatics for spatial infrastructure development in earth and allied sciences* (p. 6).

Durr, C., Constantin, J., Wagner, M. H., Navier, H., Demilly, D., Goertz, S., & Nesi, N. (2016). Virtual modelling based on deep phenotyping provides complementary data to field experiments to predict plant emergence in oilseed rape genotypes. *European Journal of Agronomy*, *79*, 90–99. https://doi.org/10.1016/j.eja.2016.06.001

Dutta, A., Patra, A., Hazra, K. K., Nath, C. P., Kumar, N., & Rakshit, A. (2022). A state of the art review in crop residue burning in India: Previous knowledge, present circumstances and future strategies. *Environmental Challenges*, *8*, 100581. https://doi.org/10.1016/j.envc.2022.100581

Dw, D. (1975). Measuring forage production of grazing units from Landsat MSS data. In *Proceedings of 10th international symposium on remote sensing of environment, 1975* (pp. 1169-1178). ERIM.

Dwivedi, B., Singh, V., Shukla, A., & Meena, M. (2012). Optimizing dry and wet tillage for rice on a Gangetic alluvial soil: Effect on soil characteristics, water use efficiency and productivity of the rice–wheat system. *European Journal of Agronomy*, *43*, 155–165. https://doi.org/10.1016/j.eja.2012.06.002

Dzotsi, K., Basso, B., & Jones, J. (2013). Development, uncertainty and sensitivity analysis of the simple SALUS crop model in DSSAT. *Ecological Modelling*, *260*, 62–76. https://doi.org/10.1016/j.ecolmodel.2013.03.017

Ebrahimirad, H., Amiri, E., Babazadeh, H., & Sedghi, H. (2018). Calibration and evaluation of CERES-rice model under different density and water managements. *Applied Ecology and Environmental Research*, *16*(5), 6469-6482.https://doi.org/10.15666/aeer/1605_64696482

Ehmke, T. (2013). Unmanned Aerial Systems for Field Scouting and Spraying. *Crops & Soils*, *46*(6), 4–9. https://doi.org/10.2134/cs2013-46-6-1

Ekka, R. E., Sarawgi, A. K., & Kanwar, R. R. (2011). Correlation and path analysis in traditional rice accessions of Chhattisgarh. *Journal of rice research*, *4*(1), 11-18.

Emeana, E. M., Trenchard, L., & Dehnen-Schmutz, K. (2020). The Revolution of Mobile Phone-Enabled Services for Agricultural Development (m-Agri Services) in Africa: The Challenges for Sustainability. *Sustainability*, *12*(2), 485. https://doi.org/ 10.3390/ su12020485

Erda, L., Wei, X., Hui, J., Yinlong, X., Yue, L., Liping, B., & Liyong, X. (2005). Climate change impacts on crop yield and quality with CO 2 fertilization in China. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1463), 2149–2154. https://doi.org/10.1098/rstb.2005.1743

Etkin, D., Kirshen, P., Watkins, D., Roncoli, C., Sanon, M., Some, L., Dembele, Y., Sanfo, J., Zoungrana, J., & Hoogenboom, G. (2015). Stochastic Programming for Improved Multiuse Reservoir Operation in Burkina Faso, West Africa. *Journal of Water Resources Planning and Management*, *141*(3). https://doi.org/10.1061/(asce)wr.1943-5452.0000396

Fagade, S. O., & De Datta, S. K. (1971). Leaf Area Index, Tillering Capacity, and Grain Yield of Tropical Rice as Affected by Plant Density and Nitrogen Level1. *Agronomy Journal*, *63*(3), 503–506. https://doi.org/10.2134/agronj1971.00021962006300030047x

Fageria, N. K. (2007). Yield Physiology of Rice. *Journal of Plant Nutrition*, *30*(6), 843–879. https://doi.org/10.1080/15226510701374831

Fahad, S., Adnan, M., Noor, M., Arif, M., Alam, M., Khan, I. A., Ullah, H., Wahid, F., Mian, I A., Jamal, Y., Basir, B., Hassan, S., Saud, S., Riaz,A. M., Wu, C., Khan, A. M. & Wang, D. (2019). Major constraints for global rice production. In *Advances in rice research for abiotic stress tolerance* (pp. 1-22). Woodhead Publishing.

FAO, Cropwat 8.0 for windows user guide. Rome, Italy, 2009.

FAO. Home | Food and Agriculture Organization of the United Nations. (n.d.). FAO 2019 Home. https://www.fao.org/home/en

FAOSTAT. (n.d.). https://www.fao.org/faostat/en-2022/#home

Farooq, M., Siddique, K. H., Rehman, H., Aziz, T., Lee, D. J., & Wahid, A. (2011). Rice direct seeding: Experiences, challenges and opportunities. *Soil and Tillage Research*, *111*(2), 87–98. https://doi.org/10.1016/j.still.2010.10.008

Feller, C. (2015). N-Expert – Fertiliser Recommendations for Field Vegetables. http:// www.igzev.de/n-expert/?lang=en . Accessed 2 April 2020.

Feller, C., Fink, M., Laber, H., Maync, A., Paschold, P. J., Scharpf, H.C., Schlaghecken, J., Strohmeyer, K., Weier, U., Ziegler, J. (2011). Fertilisation in Outdoor Vegetable Production. Version 7. July 2011. https://www.igzev.de/projekt_type/n-expertduengung-im-freilandgemuesebau/?lang=en Accessed on January 2023.

Fernandez, M. G. S., Becraft, P. W., Yin, Y., & Lübberstedt, T. (2009). From dwarves to giants? Plant height manipulation for biomass yield. *Trends in plant science*, *14*(8), 454-461.

Fey, A., & Conrad, R. (2003). Effect of temperature on the rate limiting step in the methanogenic degradation pathway in rice field soil. *Soil Biology and Biochemistry*, *35*(1), 1–8. https://doi.org/10.1016/s0038-0717(02)00175-x

Fey, A., Claus, P., & Conrad, R. (2004). Temporal change of 13C-isotope signatures and methanogenic pathways in rice field soil incubated anoxically at different temperatures. *Geochimica Et Cosmochimica Acta*, *68*(2), 293–306. https://doi.org/10.1016/s0016-7037(03)00426-5

Fontaine, S., Mariotti, A., & Abbadie, L. (2003). The priming effect of organic matter: a question of microbial competition? *Soil Biology and Biochemistry*, *35*(6), 837–843. https://doi.org/10.1016/s0038-0717(03)00123-8

Fuentes, M. M. P. B., Fish, M. R., & Maynard, J. A. (2012). Management strategies to mitigate the impacts of climate change on sea turtle's terrestrial reproductive phase. *Mitigation and Adaptation Strategies for Global Change*, *17*(1), 51-63.

Fukuda, S., Koba, K., Okamura, M., Watanabe, Y., Hosoi, J., Nakagomi, K., Maeda, H., Kondo, M., & Sugiura, D. (2021). Novel technique for non-destructive LAI estimation by continuous measurement of NIR and PAR in rice canopy. *Field Crops Research*, *263*, 108070. https://doi.org/10.1016/j.fcr.2021.108070

Gallardo, M., Elia, A., & Thompson, R. B. (2020). Decision support systems and models for aiding irrigation and nutrient management of vegetable crops. *Agricultural Water Management*, *240*, 106209. https://doi.org/10.1016/j.agwat.2020.106209

Gaydon, D., Probert, M., Buresh, R., Meinke, H., & Timsina, J. (2012). Modelling the role of algae in rice crop nutrition and soil organic carbon maintenance. *European Journal of Agronomy*, *39*, 35–43. https://doi.org/10.1016/j.eja.2012.01.004

Ghosh, M., Swain, D. K., Jha, M. K., & Tewari, V. K. (2013). Precision nitrogen management using chlorophyll meter for Improving Growth, Productivity and N Use Efficiency of Rice in Subtropical Climate. *Journal of Agricultural Science*, *5*(2). https://doi.org/10.5539/jas.v5n2p253

Gitelson, A. A., Viña, A., Ciganda, V., Rundquist, D. C., & Arkebauer, T. J. (2005). Remote estimation of canopy chlorophyll content in crops. *Geophysical Research Letters*, *32*(8). https://doi.org/10.1029/2005gl022688

Glass, A. D. M. (2003). Nitrogen Use Efficiency of Crop Plants: Physiological Constraints upon Nitrogen Absorption. *Critical Reviews in Plant Sciences*, *22*(5), 453–470. https://doi.org/ 10.1080/07352680390243512

Godwin, D. C., & Jones, A. C. (1991). Nitrogen Dynamics in Soi-Plant Systems. *Modeling plant and soil systems*, *31*, 287-321.

Godwin, D. C., & Singh, U. (1998). Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. In *Understanding options for agricultural production* (pp. 55-77). Springer, Dordrecht.

González-Fernández, A. B., Rodríguez-Pérez, J. R., Marcelo, V., & Valenciano, J. B. (2015). Using field spectrometry and a plant probe accessory to determine leaf water content in commercial vineyards. *Agricultural Water Management*, *156*, 43–50. https://doi.org/ 10.1016/ j.agwat.2015.03.024

Gopinath, G., Surendran, U., Vishak, J., Sasidharan, N., & Fasil CT, M. (2024). Hyperspectral data and vegetative indices for paddy: A case study in Kerala, India. *Remote Sensing Applications: Society and Environment*, *33*, 101109. https://doi.org/10.1016 /j.rsase. 2023.101109

Gopinath, P., Parsad, R., Joseph, B., & S., A. (2021). grapesAgri1: Collection of Shiny Apps for Data Analysis in Agriculture. *Journal of Open Source Software*, *6*(63), 3437. https://doi.org/10.21105/joss.03437

Graf, B., Gutierrez, A., Rakotobe, O., Zahner, P., & Delucchi, V. (1990). A simulation model for the dynamics of rice growth and development: Part II—The competition with weeds for nitrogen and light. *Agricultural Systems*, *32*(4), 367–392. https://doi.org/10.1016/0308-521x(90)90100-5

Graves, A. R., Hess, T., Matthews, R. B., Stephens, W., & Middleton, T. (2002). Crop Simulation Models as Tools in Computer Laboratory and Classroom-Based Education. *Journal of Natural Resources and Life Sciences Education*, *31*(1), 48–54. https://doi.org/ 10.2134/jnrlse.2002.0048

Gul, F., Ahmed, I., Ashfaq, M., Jan, D., Fahad, S., Li, X., Wang, D., Fahad, M., Fayyaz, M., & Shah, S. A. (2020). Use of crop growth model to simulate the impact of climate change on yield of various wheat cultivars under different agro-environmental conditions in Khyber Pakhtunkhwa, Pakistan. *Arabian Journal of Geosciences*, *13*(3). https://doi.org/10.1007/s12517-020-5118-1

Gumel, D. Y., Abdullah, A. M., Sood, A. M., Elhadia, R. E., Jamalani, M. A., & Youssefa, K. A. A. B. (2017). Assessing paddy rice yield sensitivity to temperature and rainfall variability in Peninsular Malaysia using DSSAT model. *International Journal of Applied Environmental Sciences*, *12*(8), 1521-1545.

Gummert, M., Nguyen-Van-Hung, Cabardo, C., Quilloy, R., Aung, Y. L., Thant, A. M., Kyaw, M. A., Labios, R., Htwe, N. M., & Singleton, G. R. (2020). Assessment of post-harvest losses and carbon footprint in intensive lowland rice production in Myanmar. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-76639-5

Gunawan, A., Purwono, Lubis, I., & Widiarta, I. N. (2023). Effect of nitrogen doses on growth and yield of several varieties of tungro-infected rice plant. *Indonesian Journal of Agronomy*, *51*(2), 190–201. https://doi.org/10.24831/ija.v51i2.46091

Guo, J., Jia, Y., Chen, H., Zhang, L., Yang, J., Zhang, J., Hu, X., Ye, X., Li, Y., & Zhou, Y. (2019). Growth, photosynthesis, and nutrient uptake in wheat are affected by differences in nitrogen levels and forms and potassium supply. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-018-37838-3

Guppy, C. N., Menzies, N. W., Moody, P. W., & Blamey, F. P. C. (2005). Competitive sorption reactions between phosphorus and organic matter in soil: a review. *Soil Research*, *43*(2), 189. https://doi.org/10.1071/sr04049

Gupta, R. K., Naresh, R. K., Hobbs, P. R., & Ladha, J. K. (2002). Adopting conservation agriculture in the rice-wheat system of the Indo-Gangetic Plains: New opportunities for saving water. In *Water wise rice production. Proceedings of the international workshop on water wise rice production* (pp. 207-222). Los Banos: International Rice Research Institute.

Gupta, R. K., Naresh, R. K., Hobbs, P. R., Jiaguo, Z., & Ladha, J. K. (2003). Sustainability of post-Green Revolution agriculture: The rice–wheat cropping systems of the Indo-Gangetic

Plains and China. *Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts*, *65*, 1-25.

Gupta, R. P., & Dakshinamoorthy, C. (1981) Procedures for physical analysis of soil and collection of agrometeorological data. Research Bulletin. ICAR, New Delhi.

Hamza, Y. G., Ameta, S. K., Tukur, A., & Usman, A. (2020). Overview on evidence and reality of climate change. *IOSR Journal of Environmental Science Toxicology Food Technology*, *14*(7), 17-26.

Haque, M. M., Biswas, J. C., Maniruzzaman, M., Hossain, M. B., & Islam, M. R. (2021). Water management and soil amendment for reducing emission factor and global warming potential but improving rice yield. *Paddy and Water Environment*. https://doi.org/10.1007/s10333-021-00851-w

Hasan, M. M., & Rahman, M. M. (2019). Simulating climate change impacts on T. aman (BR-22) rice yield: a predictive approach using DSSAT model. *Water and Environment Journal*, *34*(S1), 250–262. https://doi.org/10.1111/wej.12523

Hashimoto, K. (2019). Global Temperature and Atmospheric Carbon Dioxide Concentration. In: Global Carbon Dioxide Recycling. Springer Briefs in Energy. Springer, Singapore. https://doi.org/10.1007/978-981-13-8584-1_3

Hassan, M. S., Abul, K., Haque, M. M., & Abdul, H. (2007). Photosynthetic characters, spad value and nitrogen use efficiency of traditional Aus rice (Oryza sativa L.) cultivars. *SAARC Journal of Agriculture*, *5*(2), 31-41.

Hiltbrunner, J. (2004). *Legume living mulches for the control of weeds in organic winter wheat (Triticum aestivum L.)* (Doctoral dissertation, ETH Zurich).

Hoffmann, M. P., Odhiambo, J. J., Koch, M., Ayisi, K. K., Zhao, G., Soler, A. S., & Rötter, R. P. (2018). Exploring adaptations of groundnut cropping to prevailing climate variability and extremes in Limpopo Province, South Africa. *Field Crops Research*, *219*, 1–13. https://doi.org/10.1016/j.fcr.2018.01.019

Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., Brown, H., Whish, J.P.M., Verrall, S., Fainges, J., Bell, L.W., Peake, A.S., Poulton, P.L., Hochman, Z., Thorburn, P.J., Gaydon, D.S., & Keating, B. A. (2014). APSIM–evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software*, *62*, 327-350. https://doi.org/10.1016/j.envsoft.2014.07.009

Hoogenboom, G. (1999). The state-of-the art in crop modeling. In *Climate prediction and agriculture. Proc the START/WMO International Workshop held in Geneva, Switzerland* (pp. 27-29).

Hoogenboom, G., Jones, J. W., Wilkens, P. W., Porter, C. H., Boote, K. J., Hunt, L. A., Singh, U., Lizaso, J.I., White, J.W., Uryasev, O., Ogoshi, R., Koo, J., Shelia, V., & Tsuji, G. Y. (2015). Decision support system for agrotechnology transfer (DSSAT) Version 4.6 (http://dssat. net). DSSAT Foundation, Prosser.

Hoogenboom, G., Tsuji, G. Y., Pickering, N. B., Curry, R. B., Jones, J. W., Singh, U., & Godwin, D. C. (1995). Decision support system to study climate change impacts on crop production. *Climate change and agriculture: Analysis of potential international impacts*, *59*, 51-75.

Horie, T., Yajima, M., & Nakagawa, H. (1992). Yield forecasting. *Agricultural Systems*, *40*(1–3), 211–236. https://doi.org/10.1016/0308-521x(92)90022-g

Hossain, A., Sarkar, S., Rahman, M. A., Bhatt, R., Garai, S., Saha, S., Islam, M. T., & Meena, R. S. (2021). Ecological Intensification for Sustainable Agriculture in South Asia. *Ecological Intensification of Natural Resources for Sustainable Agriculture*, 171–213. https://doi.org/10.1007/978-981-33-4203-3_6

Hou, W., Khan, M. R., Zhang, J., Lu, J., Ren, T., Cong, R., & Li, X. (2019). Nitrogen rate and plant density interaction enhances radiation interception, yield and nitrogen use efficiency of mechanically transplanted rice. *Agriculture, Ecosystems & Environment*, *269*, 183–192. https://doi.org/10.1016/j.agee.2018.10.001

Howell, K. R., Shrestha, P., & Dodd, I. C. (2015). Alternate wetting and drying irrigation maintained rice yields despite half the irrigation volume, but is currently unlikely to be

adopted by smallholder lowland rice farmers in Nepal. *Food and Energy Security*, *4*(2), 144–157. https://doi.org/10.1002/fes3.58

Hsiao, T. C. (1973). Plant Responses to Water Stress. *Annual Review of Plant Physiology*, *24*(1), 519–570. https://doi.org/10.1146/annurev.pp.24.060173.002511

http://www.knowledgebank.irri.org/step-by-step-production/growth/water-management, Accessed on January 2024

https://apps.fas.usda.gov/psdonline/circulars/production.pdf

https://keralaagriculture.gov.in/en/2021/05/05/rice-development-2/. Accessed on January 2024

https://keralaagriculture.gov.in/en/schemes/. Accessed on January 2024

https://rvskvv.net/images/Soil-and-Plant-Analysis_17.04.2020.pdf. Accessed on January 2024

https://spb.kerala.gov.in/economic-review/ER2011/pdf/Chapter06.pdf. Accessed on January 2024

https://spb.kerala.gov.in/economic-review/ER2016/chapter02_03.php. Accessed on January 2024

https://www.indiatoday.in/india-today-insight/story/paddy-fields-vanishing-fast-how-rice-loving-kerala-is-staring-at-a-crisis-2431375-2023-09-05. Accessed on January 2024

https://www.mapsofindia.com/maps/kerala/keralaagriculture.htm. Accessed on January 2024

https://www.statista.com/topics/1443/rice/#topicHeader__wrapper, Rice - statistics & facts Published by M. Shahbandeh, Mar 2, 2022

https://www.statista.com/topics/9368/rice-market-in-india/#topicOverview. Accessed on January 2024

Huang, S., Sun, Y., Yu, X., & Zhang, W. (2015). Interactive effects of temperature and moisture on CO2 and CH4 production in a paddy soil under long-term different fertilization regimes. *Biology and Fertility of Soils*, *52*(3), 285–294. https://doi.org/10.1007/s00374-015-1075-3

Huber, M., Julkowska, M. M., Snoek, L. B., van Veen, H., Toulotte, J., Kumar, V., Kajala, K., Sasidharan, R., & Pierik, R. (2023). Towards increased shading capacity: A combined phenotypic and genetic analysis of rice shoot architecture *Plants, People, Planet*, *6*(1), 128–147. https://doi.org/10.1002/ppp3.10419

Hussain, A., Bhat, M. A., & Ganie, M. A. (2001). Effect of number and age of seedlings on growth, yield, nutrient uptake and economics of rice (Oryza sativa) under system of rice intensification in temperate conditions. *Indian Journal of Agronomy*, *57*(2), 133–137. https://doi.org/10.59797/ija.v57i2.4625

Hussain, T., & Farooq, S. (2023). Coco-Peat, a Sustainable Vertical Gardening Option for Urban Areas. *Pakistan Journal of Social Sciences*, *43*(3), 435-440.

Incrocci, L., Dimauro, B., Santamaria, P., & Pardossi, A. (2013). La concimazione azotata degli ortaggi.

Inoue, Y., Peñuelas, J., Miyata, A., & Mano, M. (2008). Normalized difference spectral indices for estimating photosynthetic efficiency and capacity at a canopy scale derived from hyperspectral and CO2 flux measurements in rice. *Remote Sensing of Environment*, *112*(1), 156-172. https://doi.org/10.1016/j.rse.2007.04.011

International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) (1993) The IBSNAT decade. Ten years of endeavor at the frontier of science and technology. Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, Hawaii.

IPCC (2007a) Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (S Solomon, D Qin, M Manning, et al (eds)). Cambridge, UK, and New York: Cambridge University Press. http://www.ipcc.ch. (WGI).

IPCC (2007b) Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (ML Parry, OF Canziani, JP Palutikof, et al (eds)). Cambridge, UK, and New York: Cambridge University Press. http://www.ipcc.ch. (WGII).

Ishfaq, M., Farooq, M., Zulfiqar, U., Hussain, S., Akbar, N., Nawaz, A., & Anjum, S. A. (2020). Alternate wetting and drying: A water-saving and ecofriendly rice production system. *Agricultural Water Management*, 241, 106363. https://doi.org/10.1016/ j.agwat. 2020.106363

Ishimaru, K., Hirotsu, N., Madoka, Y., Murakami, N., Hara, N., Onodera, H., Kashiwagi, T., Ujiie, K., Shimizu, B. I., Onishi, A., Miyagawa, H., & Katoh, E. (2013). Loss of function of the IAA-glucose hydrolase gene TGW6 enhances rice grain weight and increases yield. *Nature Genetics*, *45*(6), 707–711. https://doi.org/10.1038/ng.2612

Islam, S. S., & Hasan, A. K. (2021). Determination of Upland Rice Cultivar Coefficient Specific Parameters for DSSAT (Version 4.7)-CERES-Rice Crop Simulation Model and Evaluation of the Crop Model under Different Temperature Treatments conditions. *American Journal of Plant Sciences*, *12*(5), 782-795.

Ito, O., & Watanabe, I. (1985). Availability to Rice Plants of Nitrogen Fixed by Azolla. *Soil Science and Plant Nutrition*, *31*(1), 91–104. https://doi.org/ 10.1080/ 17470765. 1985.10555220

Jackson, M. L. (1973). *Soil Chemical Analysis*. http://books.google.ie/ books? id= SBPhAAAAMAAJ&q=Jackson,+M.+L.+(1967)+Soil+chemical+analysis.&dq=Jackson,+M.+L.+(1967)+Soil+chemical+analysis.&hl=&cd=1&source=gbs_api

Jame, Y. W., & Cutforth, H. W. (1996). Crop growth models for decision support systems. *Canadian Journal of Plant Science*, *76*(1), 9–19. https://doi.org/10.4141/cjps96-003

Jayakumar, M., Rajavel, M., & Surendran, U. (2016). Climate-based statistical regression models for crop yield forecasting of coffee in humid tropical Kerala, India. *International Journal of Biometeorology*, *60*(12), 1943–1952. https://doi.org/10.1007/s00484-016-1181-4

Jayakumar, M., Rajavel, M., Surendran, U., Gopinath, G., & Ramamoorthy, K. (2017). Impact of climate variability on coffee yield in India—with a micro-level case study using long-term coffee yield data of humid tropical Kerala. *Climatic Change*, *145*(3–4), 335–349. https://doi.org/10.1007/s10584-017-2101-2

Jayakumar, M., Sruthi, P., Surendran, U., Safari, Z., & Ahammed, S. J. (2023). The Impact of Agricultural Chemicals on the Environment and Human Health in India: A Review. *Knowledge-Based Engineering and Sciences*, *4*(2), 60-72.

Jeong, H., Jang, T., Seong, C., & Park, S. (2014). Assessing nitrogen fertilizer rates and split applications using the DSSAT model for rice irrigated with urban wastewater. *Agricultural Water Management*, *141*, 1–9. https://doi.org/10.1016/j.agwat.2014.04.009

Jha, P. K., Athanasiadis, P., Gualdi, S., Trabucco, A., Mereu, V., Shelia, V., & Hoogenboom, G. (2019). Using daily data from seasonal forecasts in dynamic crop models for yield prediction: A case study for rice in Nepal's Terai. *Agricultural and forest meteorology*, *265*, 349-358. https://doi.org/10.1016/j.agrformet.2018.11.029

Jha, P. K., Ines, A. V., Han, E., Cruz, R., & Vara Prasad, P. (2022). A comparison of multiple calibration and ensembling methods for estimating genetic coefficients of CERES-Rice to simulate phenology and yields. *Field Crops Research*, *284*, 108560. https://doi.org/10.1016/j.fcr.2022.108560

Jha, R. K., Kalita, P. K., & Jat, R. (2020). Development of production management strategies for a long-duration rice variety: Rajendra Mahsuri—using crop growth model, DSSAT, for the state of Bihar, India. *Paddy and Water Environment*, *18*(3), 531–545. https://doi.org/10.1007/s10333-020-00799-3

Jiang, S., Du, B., Wu, Q., Zhang, H., & Zhu, J. (2023). Increasing pit-planting density of rice varieties with different panicle types to improves sink characteristics and rice yield under alternate wetting and drying irrigation. *Food and Energy Security*, *12*(1), https://doi.org/10.1002/fes3.335

Jiang, Z., Yang, S., Ding, J., Sun, X., Chen, X., Liu, X., & Xu, J. (2021). Modeling Climate Change Effects on Rice Yield and Soil Carbon Under Variable Water and Nutrient Management. *Sustainability*, 13(2), 568. https://doi.org/10.3390/su13020568

Jones, J. W., Antle, J. M., Basso, B., Boote, K. J., Conant, R. T., Foster, I., Godfray, H. C. J., Herrero, M., Howitt, R. E., Janssen, S., Keating, B. A., Munoz-Carpena, R., Porter, C. H., Rosenzweig, C., & Wheeler, T. R. (2017). Toward a new generation of agricultural system data, models, and knowledge products: State of agricultural systems science. *Agricultural Systems*, *155*, 269–288. https://doi.org/10.1016/j.agsy.2016.09.021

Jones, J. W., Tsuji, G. Y., Hoogenboom, G., Hunt, L. A., Thornton, P. K., Wilkens, P. W., Imamura, D.T., Bowen, W.T., & Singh, U. (1998). Decision support system for

agrotechnology transfer: DSSAT v3. In *Understanding options for agricultural production* (pp. 157-177). Springer, Dordrecht.

Jones, J., Hoogenboom, G., Porter, C., Boote, K., Batchelor, W., Hunt, L., Wilkens, P., Singh, U., Gijsman, A., & Ritchie, J. (2003). The DSSAT cropping system model. *European Journal of Agronomy*, *18*(3–4), 235–265. https://doi.org/10.1016/s1161-0301(02)00107-7

Jonoski, A., Alfonso, L., Almoradie, A., Popescu, I., van Andel, S. J., & Vojinovic, Z. (2012). Mobile phone applications in the water domain. *Environmental Engineering & Management Journal (EEMJ)*, *11*(5).

Joseph, E. J. (2011). *Climate change and sustainable water resources management in Kerala*. Centre for Water Resources Development and Management.

Jumadi, O., Hiola, S. F., Hala, Y., Norton, J., & Inubushi, K. (2014). Influence of Azolla (Azolla microphylla Kaulf.) compost on biogenic gas production, inorganic nitrogen and growth of upland kangkong (Ipomoea aquatica Forsk.) in a silt loam soil. *Soil Science and Plant Nutrition*, *60*(5), 722-730. https://doi.org/10.1080/00380768.2014.942879

Juraimi, A. S., Saiful, M., Begum, M., Anuar, A. R., & Azmi, M. (2009). Influence of flooding intensity and duration on rice growth and yield. *Pertanika Journal of. Tropical. Agricultural Sci*ence *32*(2), 195-208.

Kadiyala, M. D. M., Jones, J. W., Mylavarapu, R. S., Li, Y. C., & Reddy, M. D. (2015b). Identifying irrigation and nitrogen best management practices for aerobic rice–maize cropping system for semi-arid tropics using CERES-rice and maize models. *Agricultural Water Management*, 149, 23–32. https://doi.org/10.1016/j.agwat.2014.10.019

Kadiyala, M. D. M., Nedumaran, S., Singh, P., Chukka, S., Irshad, M. A., & Bantilan, M. C. S. (2015a). An integrated crop model and GIS decision support system for assisting agronomic decision making under climate change. *Science of the Total Environment*, *521*, 123-134. https://doi.org/10.1016/j.scitotenv.2015.03.097

Kaiser, E., Morales, A., Harbinson, J., Kromdijk, J., Heuvelink, E., & Marcelis, L. F. M. (2014). Dynamic photosynthesis in different environmental conditions. *Journal of Experimental Botany*, *66*(9), 2415–2426. https://doi.org/10.1093/jxb/eru406

Kamruzzaman, M., Kayum, M. A., Hasan, M. M., Hasan, M. M., & Silva, J. A. T. D. (2014). Effect of split application of nitrogen fertilizer on yield and yield attributes of transplanted aman rice (Oryza sativa L.). *Bangladesh Journal of Agricultural Research*, *38*(4), 579–587. https://doi.org/10.3329/bjar.v38i4.18886

Kant, K., Bora, P. K., & Saikia, U. S. (2018). Calibration of DSSAT-CERES-Rice model for rice cultivars under different N-levels in Meghalaya, India. *Journal of Agrometeorology*, *20*(4), 322-324. https://doi.org/10.54386/jam.v20i4.575

Kasampalis, D., Alexandridis, T., Deva, C., Challinor, A., Moshou, D., & Zalidis, G. (2018). Contribution of Remote Sensing on Crop Models: A Review. *Journal of Imaging*, *4*(4), 52. https://doi.org/10.3390/jimaging4040052

Kaspary, T. E., Roma-Burgos, N., & Merotto, A. (2020). Snorkeling Strategy: Tolerance to Flooding in Rice and Potential Application for Weed Management. *Genes*, *11*(9), 975. https://doi.org/10.3390/genes11090975

Kavitha, M., Paramaguru, P., & Maheswari, M. U. (2020). Doubling farmers income through system of rice intensification and comparative analysis of SRI and conventional method of rice cultivation in Theni district of Tamil Nadu. *International Journal of Chemical Studies*, *8*(4), 414–416. https://doi.org/10.22271/chemi.2020.v8.i4g.10180

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., & Smith, C. J. (2003a). An overview of APSIM, a model designed for farming systems simulation. *European journal of agronomy*, *18*(3-4), 267-288. https://doi.org/10.1016/s1161-0301(02)00108-9

Keating, B., Gaydon, D., Huth, N., Probert, M., Verburg, K., Smith, C., & Bond, W. (2002,). Use of modelling to explore the water balance of dryland farming systems in the Murray-

Darling Basin, Australia. *European Journal of Agronomy*, *18*(1–2), 159–169. https://doi.org/10.1016/s1161-0301(02)00102-8

Kephe, P. N., Ayisi, K. K., & Petja, B. M. (2021). Challenges and opportunities in crop simulation modelling under seasonal and projected climate change scenarios for crop production in South Africa. *Agriculture & Food Security*, *10*(1). https://doi.org/10.1186/s40066-020-00283-5

Kerala Agricultural University (KAU) (2016) Package of Practices Recommendations Kerala Agricultural University, Thrissur, Kerala

http://www.kerenvis.nic.in/Database/Agriculture_828.aspx accessed on 26th July 2018

Keuskamp, J. A., Dingemans, B. J., Lehtinen, T., Sarneel, J. M., & Hefting, M. M. (2013). Tea Bag Index: a novel approach to collect uniform decomposition data across ecosystems. *Methods in Ecology and Evolution*, *4*(11), 1070-1075.

Khan, G. R., Akmal, M., Ali, N., Goher, R., Anjum, M. M., & Wahid, F. (2022). Effect of Different Nitrogen Rates and Split Applications on Growth and Productivity of Wheat Cultivars. *Gesunde Pflanzen*, *74*(3), 523–538. https://doi.org/10.1007/s10343-022-00628-z

Khan, I., Fahad, S., Wu, L., Zhou, W., Xu, P., Sun, Z., Salam, A., Imran, M., Jiang, M., Kuzyakov, Y., & Hu, R. (2019). Labile organic matter intensifies phosphorous mobilization in paddy soils by microbial iron (III) reduction. *Geoderma*, *352*, 185–196. https://doi.org/10.1016/j.geoderma.2019.06.011

Khan, M. I., & Walker, D. (2015). Application of crop growth simulation models in agriculture with special reference to water management planning. *International Journal Of Core Engineering & Management*, *2*(5), 113-130.

Kingra, P. K., Kaur, R., & Kaur, S. (2019). Climate change impacts on rice (Oryza sativa) productivity and strategies for its sustainable management. *The Indian Journal of Agricultural Sciences*, *89*(2), 171-180. https://doi.org/10.56093/ijas.v89i2.86981

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J. G., Dlugokencky, E. J., Bergamaschi, P., Bergmann, D., Blake, D. R., Bruhwiler, L., Cameron-Smith, P., Castaldi, S., Chevallier, F., Feng, L., Fraser, A., Heimann, M., Hodson, E. L., Houweling, S., Josse, B., Fraser, P. J., Krummel, P. B., Lamarque, J., Langenfelds, R.L., Le Quéré, C., Naik, V., O'Doherty, S., Palmer, P., Pison, I., Plummer, D., Poulter, B., Prinn, R. G., Rigby, M., Ringeval, B., Santini, M., Schmidt, M., Shindell, D. T., Simpson, I. J., Spahni, R., Steele,L. P., Strode, S.A., Sudo, K., Szopa, S., van der Werf, G. R., Voulgarakis, A., van Weele, M., Weiss, R. F., Williams, J. E., & Zeng, G. (2013). Three decades of global methane sources and sinks. *Nature Geoscience*, *6*(10), 813–823. https://doi.org/10.1038/ngeo1955

Kobayashi, K. (1994). A very simple model of crop growth: derivation and application. Japan Proceedings of the 1994 National Conference of the Agricultural Meteorological Society, 392-393.

Kropff, M. J., Teng, P. S., Aggarwal, P. K., Bouma, J., Bouman, B. A. M., Jones, J. W., & van Laar, H. H. (Eds.) (1996). *Applications of Systems Approaches at the Field Level, Volume 2.* Kluwer Academic Publishers.

Kropff, M. J., Van Laar, H. H., & Matthews, R. B. (1994). ORYZA1: An ecophysiological model for irrigated rice production.

Kulak, M. A. (2014). *Improving eco-efficiency of low-input cropping systems by the use of life cycle assessment and integrative approach* (Doctoral dissertation, ETH Zurich).

Kumar, S. N., & Aggarwal, P. K. (2013). Climate change and coconut plantations in India: Impacts and potential adaptation gains. *Agricultural Systems*, *117*, 45-54. https://doi.org/10.1016/j.agsy.2013.01.001

Kumar, V., & Ladha, J. K. (2011). Direct seeding of rice: recent developments and future research needs. *Advances in agronomy*, *111*, 297-413.

Kumar, V., Naresh, R., Tomar, V., Kumar, R., vek, V., Kumar, R., Yadav, R., Mahajan, N., Singh, A., Singh, S., Chandra, S., & Yadav, O. S. (2019). Growth, Yield and Water Productivity of Scented Rice (Oryza sativa L.) as Influenced by Planting Techniques and Integrated Nutrient Management Practice. *International Journal of Current Microbiology and Applied Sciences*, *8*(06), 1369–1380. https://doi.org/10.20546/ijcmas.2019.806.166

Landivar, J. A., Baker, D. N., & Jenkins, J. N. (1983). Application of GOSSYM to Genetic Feasibility Studies. II. Analyses of Increasing Photosynthesis, Specific Leaf Weight and Longevity of Leaves in Cotton 1. *Crop Science*, *23*(3), 504-510.

Langer, R. H. M., & Liew, F. K. Y. (1973). Effects of varying nitrogen supply at different stages of the reproductive phase on spikelet and grain production and on grain nitrogen in wheat. *Australian Journal of Agricultural Research*, *24*(5), 647-656.

Le Quéré, C., Andres, R. J., Boden, T., Conway, T., Houghton, R. A., House, J. I., Marland, G., Peters, G. P., van der Werf, G. R., Ahlström, A., Andrew, R. M., Bopp, L., Canadell, J. G., Ciais, P., Doney, S. C., Enright, C., Friedlingstein, P., Huntingford, C., Jain, A. K., Jourdain, C., Kato, E., Keeling, R. F., Klein Goldewijk, K., Levis, S., Levy, P., Lomas, M., Poulter, B., Raupach, M. R., Schwinger, J., Sitch, S., Stocker, B. D., Viovy, N., Zaehle, S., & Zeng, N. (2013). The global carbon budget 1959–2011. *Earth System Science Data*, *5*(1), 165–185. https://doi.org/10.5194/essd-5-165-2013

Lee, H., Hwang, W., Jeong, J., Yang, S., Jeong, N., Lee, C., & Choi, M. (2021). Physiological causes of transplantation shock on rice growth inhibition and delayed heading. *Scientific reports*, *11*(1), 16818.

Leghari, S. J., Wahocho, N. A., Laghari, G. M., HafeezLaghari, A., MustafaBhabhan, G., HussainTalpur, K., & Lashari, A. A. (2016). Role of nitrogen for plant growth and development: A review. *Advances in Environmental Biology*, *10*(9), 209-219.

Li, J., Song, J., Li, M., Shang, S., Mao, X., Yang, J., & Adeloye, A. J. (2018). Optimization of irrigation scheduling for spring wheat based on simulation-optimization model under uncertainty. *Agricultural water management*, *208*, 245-260.

Li, S., Fleisher, D., Timlin, D., Reddy, V. R., Wang, Z., & McClung, A. (2020). Evaluation of Different Crop Models for Simulating Rice Development and Yield in the US Mississippi Delta. *Agronomy*, *10*(12), 1905.

Li, X., Dong, J., Zhu, W., Zhao, J., & Zhou, L. (2023). Progress in the study of functional genes related to direct seeding of rice. *Molecular Breeding*, *43*(6), 46.

Li, Y., Shahbaz, M., Zhu, Z., Deng, Y., Tong, Y., Chen, L., Wu, J., & Ge, T. (2021). Oxygen availability determines key regulators in soil organic carbon mineralisation in paddy soils. *Soil Biology and Biochemistry*, *153*, 108106. https://doi.org/ 10.1016/ j.soilbio. 2020.108106

Li, Z. T., Yang, J. Y., Drury, C. F., & Hoogenboom, G. (2015). Evaluation of the DSSAT-CSM for simulating yield and soil organic C and N of a long-term maize and wheat rotation experiment in the Loess Plateau of Northwestern China. *Agricultural Systems*, 135, 90-104.

Liang, H., Hu, K., Batchelor, W. D., Qi, Z., & Li, B. (2016). An integrated soil-crop system model for water and nitrogen management in North China. *Scientific reports*, *6*(1), 1-20.

Lima, M. A. D., Faria Vieira, R., Barreto Luiz, A. J., & Haddad Galvão, J. A. (2023). CH_4 and N_2O fluxes during paddy rice crop development, post-harvest, and fallow. *Agronomía Colombiana*, *41*(1), e107053. https://doi.org/10.15446/agron.colomb.v41n1.107053

Lin, T. S., & Jain, A. K. (2022). Assessment of Climate Change Impact on Rice Production Over South and Southeast Asia Under CMIP6 Climate Scenarios. In *Remote Sensing of Agriculture and Land Cover/Land Use Changes in South and Southeast Asian Countries* (pp. 367-379). Cham: Springer International Publishing.

Linquist, B. A., Ruark, M. D., Mutters, R., Greer, C., & Hill, J. E. (2014). Nutrients and sediments in surface runoff water from direct-seeded rice fields: Implications for nutrient budgets and water quality. *Journal of Environmental Quality*, *43*(5), 1725-1735.

Linquist, B., Van Groenigen, K. J., Adviento-Borbe, M. A., Pittelkow, C., & Van Kessel, C. (2012). An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology*, *18*(1), 194-209.

Liu, H., Zhan, J., Hussain, S., & Nie, L. (2019). Grain yield and resource use efficiencies of upland and lowland rice cultivars under aerobic cultivation. *Agronomy*, *9*(10), 591.

Liu, L., Chen, T., Wang, Z., Zhang, H., Yang, J., & Zhang, J. (2013). Combination of site-specific nitrogen management and alternate wetting and drying irrigation increases grain yield and nitrogen and water use efficiency in super rice. *Field Crops Research*, *154*, 226-235.

Liu, Q., Yin, C., Li, X., He, C., Ding, Z., & Du, X. (2022). Lodging resistance of rice plants studied from the perspective of culm mechanical properties, carbon framework, free volume, and chemical composition. *Scientific Reports*, *12*(1), 20026.

Liu, Y., Ding, Y., Wang, Q., Meng, D., & Wang, S. (2011). Effects of nitrogen and 6-benzylaminopurine on rice tiller bud growth and changes in endogenous hormones and nitrogen. *Crop science*, *51*(2), 786-792.

Lu, W., Zha, Q., Zhang, H., Chen, H. Y., Yu, J., Tu, F., & Ruan, H. (2021). Changes in soil microbial communities and priming effects induced by rice straw pyrogenic organic matter produced at two temperatures. *Geoderma*, *400*, 115217. https://doi.org/10.1016 / j.geoderma. 2021.115217

Lu, X., Wang, H., Xiang, Y., Wang, Q., Su, T., Gong, R., Zhang, H., Zhu, L., Li, E., & Abdelghany, A. E. (2022b). Determination of Nitrogen Application Ratio and Sowing Time for Improving the Future Yield of Double-Harvest Rice in Nanchang Based on the DSSAT-CERES-Rice Model. *Agronomy*, *12*(12), 3199. https://doi.org/10.3390/ agronomy 12123199

Lu, Y., Wei, C., McCabe, M. F., & Sheffield, J. (2022a). Multi-variable assimilation into a modified AquaCrop model for improved maize simulation without management or crop phenology information. *Agricultural Water Management*, *266*, 107576.

Machet, J. M., Dubrulle, P., Damay, N., Duval, R., Julien, J. L., & Recous, S. (2017). A dynamic decision-making tool for calculating the optimal rates of N application for 40 annual crops while minimising the residual level of mineral N at harvest. *Agronomy*, *7*(4), 73.

Mahapatra, I. C., & Patrick, W. H. (1969). Inorganic phosphate transformation in waterlogged soils. *Soil Science*, *107*(4), 281–288. https://doi.org/10.1097/00010694-196904000-00008

Makino, A. (2021). Photosynthesis improvement for enhancing productivity in rice. *Soil Science and Plant Nutrition*, *67*(5), 513-519.

Mandal, B., Vlek, P. L. G., & Mandal, L. N. (1999). Beneficial effects of blue-green algae and Azolla, excluding supplying nitrogen, on wetland rice fields: a review. *Biology and Fertility of Soils*, *28*, 329-342.

Mandal, K. G., Kundu, D. K., Thakur, A. K., Kannan, K., Brahmanand, P. S., & Kumar, A. (2013). Aerobic rice response to irrigation regimes and fertilizer nitrogen rates. *Journal of Food, Agriculture and Environment*, *11*, 1148-1153.

Manikanta, C. L., Beena, R., Stephen, R., Manju, R. V., Viji, M. M., & Alex, S. (2020). Physio morphological plasticity of rice (Oryza sativa L.) genotypes exposed to water-stress. *Journal of Tropical Agriculture*, *58*(1).

Maniruzzaman, M., Talukder, M. S. U., Khan, M. H., Biswas, J. C., & Nemes, A. (2015). Validation of the AquaCrop model for irrigated rice production under varied water regimes in Bangladesh. *Agricultural Water Management*, *159*, 331-340.

Mannini, P., Genovesi, R., & Letterio, T. (2013). IRRINET: large scale DSS application for on-farm irrigation scheduling. *Procedia Environmental Sciences*, *19*, 823-829.

Mao, X., Jia, J., Liu, C., & Hou, Z. (2005). A simulation and prediction of agricultural irrigation on groundwater in well irrigation area of the piedmont of Mt. Taihang, North China. *Hydrological Processes: An International Journal*, *19*(10), 2071-2084.

Marcinkowski, P., & Piniewski, M. (2024). Future changes in crop yield over Poland driven by climate change, increasing atmospheric CO2 and nitrogen stress. *Agricultural Systems*, *213*, 103813.

Martínez-Eixarch, M., Alcaraz, C., Viñas, M., Noguerol, J., Aranda, X., Prenafeta-Boldú, F. X., Saldaña-De la Vega, J. A., Català, M. D. M., & Ibáñez, C. (2018). Neglecting the fallow season can significantly underestimate annual methane emissions in Mediterranean rice fields. *PLOS ONE*, *13*(5), e0198081. https://doi.org/10.1371/journal.pone.0198081

Martínez-Eixarch, M., Alcaraz, C., Viñas, M., Noguerol, J., Aranda, X., Prenafeta-Boldú, F. X., Català-Forner, M., Fennessy, M. S., & Ibáñez, C. (2021). The main drivers of methane emissions differ in the growing and flooded fallow seasons in Mediterranean rice fields. *Plant and Soil*, *460*(1–2), 211–227. https://doi.org/10.1007/s11104-020-04809-5

Massey, J. H., Walker, T. W., Anders, M. M., Smith, M. C., & Avila, L. A. (2014). Farmer adaptation of intermittent flooding using multiple-inlet rice irrigation in Mississippi. *Agricultural Water Management*, *146*, 297-304.

Matthews, R., Stephens, W., Hess, T., Middleton, T., & Graves, A. (2002). Applications of crop/soil simulation models in tropical agricultural systems.

Mboyerwa, P. A., Kibret, K., Mtakwa, P., & Aschalew, A. (2022). Rice yield and nitrogen use efficiency with system of rice intensification and conventional management practices in Mkindo Irrigation Scheme, Tanzania. *Frontiers in Sustainable Food Systems*, *6*, 802267.

Mekonnen, Y., Namuduri, S., Burton, L., Sarwat, A., & Bhansali, S. (2019). Machine learning techniques in wireless sensor network based precision agriculture. *Journal of the Electrochemical Society*, 167(3), 037522.

Mirás-Avalos, J. M., Rubio-Asensio, J. S., Ramírez-Cuesta, J. M., Maestre-Valero, J. F., & Intrigliolo, D. S. (2019). Irrigation-Advisor—A Decision Support System for Irrigation of Vegetable Crops. *Water*, *11*(11), 2245.

Mishra, A., Ketelaar, J. W., Uphoff, N., & Whitten, M. (2021). Food security and climate-smart agriculture in the lower Mekong basin of Southeast Asia: evaluating impacts of system of rice intensification with special reference to rainfed agriculture. *International Journal of Agricultural Sustainability*, *19*(2), 152-174.

Mishra, A., Singh, R., Raghuwanshi, N. S., Chatterjee, C., & Froebrich, J. (2013). Spatial variability of climate change impacts on yield of rice and wheat in the Indian Ganga Basin. *Science of the Total Environment*, *468*, S132-S138.

Mohapatra, P. K. (2013). A physiological approach to design rice panicle architecture in the quest for high grain yield. *International dialogue on perception and prospects of designer rice'.(Eds K Muralidharan, EA Siddiq) pp*, 131-142.

Molina-Martínez, J. M., & Ruiz-Canales, A. (2009). Pocket PC software to evaluate drip irrigation lateral diameters with on-line emitters. *Computers and electronics in agriculture*, *69*(1), 112-115.

Mon, Y. (2018). *Evaluation on adaptation of cut stem transplant (A Sit Phyat) method of rice practice in flood prone area* (Doctoral dissertation, MERAL Portal).

Monaco, S., Volante, A., Orasen, G., Cochrane, N., Oliver, V., Price, A. H., Teh, Y. A., Martínez-Eixarch, M., Thomas, C., Courtois, B., & Valé, G. (2021). Effects of the application of a moderate alternate wetting and drying technique on the performance of different European varieties in Northern Italy rice system. *Field Crops Research*, *270*, 108220. https://doi.org/10.1016/j.fcr.2021.108220

Montoro, A., López-Fuster, P., & Fereres, E. (2011). Improving on-farm water management through an irrigation scheduling service. *Irrigation Science*, *29*(4), 311-319.

Montoya, F., Camargo, D., Córcoles, J. I., Domínguez, A., & Ortega, J. F. (2019). Analysis of deficit irrigation strategies by using SUBSTOR-Potato model in a semi-arid area. *The Journal of Agricultural Science,* 157(7-8), 578-591.

Muangprakhon, R., & Kaewplang, S. (2021). Estimation of paddy rice plant height using UAV remote sensing. *Engineering Access*, *7*(2), 93-97.

Murthy, V. R. K. (2004). Crop growth modeling and its applications in agricultural meteorology. *Satellite remote sensing and GIS applications in agricultural meteorology*, *235*.

Myneni, R. B., & Williams, D. L. (1994). On the relationship between FAPAR and NDVI. *Remote Sensing of Environment*, *49*(3), 200-211.

Mzengeza, T. (2010). *Genetic studies of grain and morphological traits in early generation crosses of Malawi rice (Oryza sativa L.) Landraces and NERICA varieties* (Doctoral dissertation).

Nagamani, K., & Mariappan, V. N. (2017). Biosciences and Plant Biology. International Journal of Current Research in Bioscience and Plant Biology, 4(8), 80-92. https://doi.org/ 10.20546/ ijcrbp.2017.408.011

Nagargade, M., Singh, M. K., & Tyagi, V. (2018). Ecologically sustainable integrated weed management in dry and irrigated direct-seeded rice. *Advance. Plants Agricultural. Research*, *8*, 319-331.

Naresh Kumar, S., Hebbar, K. B., Kasturi Bai, K. V., & Rajagopal, V. (2018). Physiology and Biochemistry. *The Coconut Palm (Cocos nucifera L.)-Research and Development Perspectives*, 443-488.

Naser, H. M., Nagata, O., Sultana, S., & Hatano, R. (2019). Carbon sequestration and contribution of CO2, CH4 and N2O fluxes to global warming potential from paddy-fallow fields on mineral soil beneath peat in Central Hokkaido, Japan. *Agriculture*, *10*(1), 6.

Nawaz, A., Awan, M. I., Ijaz, M., Hussain, M., Ahmad, S., & Farooq, M. (2019). Direct seeding in rice: problems and prospects. *Agronomic Crops: Volume 1: Production Technologies*, 199-222.

Nayak, S., Prasanna, R., Pabby, A., Dominic, T. K., & Singh, P. K. (2004). Effect of urea, blue green algae and Azolla on nitrogen fixation and chlorophyll accumulation in soil under rice. *Biology and fertility of soils*, *40*, 67-72.

Nazir, S. F., Singh, L., Shah, B. A., & Ali, O. R. I. (2020). Rice-Wheat cropping system under changing climate scenario: A review. *IJCS*, 8(2), 1907-1914.

NBSS and LUP, (1990). Soil resources of Tamil Nadu for land use planning- detailed report, Banglore center.

Neto, M. C. L., Carvalho, F. E., Souza, G. M., & Silveira, J. A. (2021). Understanding photosynthesis in a spatial–temporal multiscale: The need for a systemic view. *Theoretical and Experimental Plant Physiology*, *33*, 113-124.

Neue, H. U., Wassmann, R., Lantin, R. S., Alberto, M. C., Aduna, J. B., & Javellana, A. M. (1996). Factors affecting methane emission from rice fields. *Atmospheric Environment*, *30*(10-11), 1751-1754.

Nguyen, T. T., Bonetti, J., Rogers, K., & Woodroffe, C. D. (2016). Indicator-based assessment of climate-change impacts on coasts: A review of concepts, methodological approaches and vulnerability indices. *Ocean & Coastal Management*, *123*, 18–43. https://doi.org/10.1016/j.ocecoaman.2015.11.022

Nirmala, B., Tuti, M. D., Mahender Kumar, R., Waris, A., Muthuraman, P., Parmar, B., & Vidhan Singh, T. (2021). Integrated assessment of system of rice intensification vs. conventional method of transplanting for economic benefit, energy efficiency and lower global warming potential in India. *Agroecology and Sustainable Food Systems*, *45*(5), 745-766.

Noguera, P., Abad, M., Noguera, V., Puchades, R., & Maquieira, A. (1998). Coconut coir waste, a new and viable ecologically-friendly peat substitute. In *XXV International Horticultural Congress, Part 7: Quality of Horticultural Products 517* (pp. 279-286).

Norton, G. J., Shafaei, M., Travis, A. J., Deacon, C. M., Danku, J., Pond, D., Cochrane, N., Lockhart, K., Salt, D., Zhang, H., Dodd, I. C., Hossain, M., Islam, M. R., & Price, A. H. (2017). Impact of alternate wetting and drying on rice physiology, grain production, and grain quality. *Field Crops Research*, *205*, 1–13. https://doi.org/ 10.1016/ j.fcr. 2017. 01.016

Novair, S. B., Hosseini, H. M., Etesami, H., & Razavipour, T. (2020). Rice straw and composted azolla alter carbon and nitrogen mineralization and microbial activity of a paddy soil under drying–rewetting cycles. *Applied Soil Ecology*, *154*, 103638.

Nyang'Au, W. O., Mati, B. M., Kalamwa, K., Wanjogu, R. K., & Kiplagat, L. K. (2014). Estimating rice yield under changing weather conditions in Kenya using CERES rice model. *International Journal of Agronomy*, *2014*.

O. Rauff, K., & Bello, R. (2015). A Review of Crop Growth Simulation Models as Tools for Agricultural Meteorology. *Agricultural Sciences*, *06*(09), 1098–1105. https://doi.org/ 10.4236/ as.2015.69105

Ohyama, T. (2010). Nitrogen as a major essential element of plants. *Nitrogen Assim. Plants*, *37*, 1-17.

Olberz, M., Kahlen, K., & Zinkernagel, J. (2018). Assessing the impact of reference evapotranspiration models on decision support systems for irrigation. *Horticulturae*, *4*(4), 49.

Orhan, O. (2021). Land suitability determination for citrus cultivation using a GIS-based multi-criteria analysis in Mersin, Turkey. *Computers and Electronics in Agriculture*, *190*, 106433.

Osakabe, Y., Osakabe, K., Shinozaki, K., & Tran, L. S. P. (2014). Response of plants to water stress. *Frontiers in plant science*, *5*, 86.

Oteng-Darko, P., Kyei-Baffour, N., & Ofori, E. (2012). Simulating rice yields under climate change scenarios using the CERES-Rice model. *African Crop Science Journal*, *20*, 401-408.

Oteng-Darko, P., Yeboah, S., Addy, S. N. T., Amponsah, S., & Danquah, E. O. (2013). Crop modeling: A tool for agricultural research–A review.

Otero, G., & Pechlaner, G. (2021). 2. Latin American Agriculture, Food, and Biotechnology: Temperate Dietary Pattern Adoption and Unsustainability. In *Food for the Few* (pp. 31-60). University of Texas Press.

Pandey, V., & Shukla, A. (2015). Acclimation and Tolerance Strategies of Rice under Drought Stress. *Rice Science*, *22*(4), 147–161. https://doi.org/10.1016/j.rsci.2015.04.001

Panse, V. G., & Sukhatme, P. V. (1954). Statistical methods for agricultural workers. *Statistical methods for agricultural workers.*

Parihar, S. S. (2004). Effect of crop-establishment method, tillage, irrigation and nitrogen on production potential of rice (Oryza sativa)-wheat (Triticum aestivum) cropping system. *Indian Journal of Agronomy*, *49*(1), 1-5.

Pasuquin, J. M., Pampolino, M. F., Witt, C., Dobermann, A., Oberthür, T., Fisher, M. J., & Inubushi, K. (2014). Closing yield gaps in maize production in Southeast Asia through site-specific nutrient management. *Field Crops Research*, *156*, 219-230.

Pathak, H. C., & Patel, M. S. (1989). Genetic variability and character association studies in upland rice (Oryza sativa L.). *GAU Res. J*, *14*(2), 31-41.

Pathak, H., Ladha, J., Aggarwal, P., Peng, S., Das, S., Singh, Y., Singh, B., Kamra, S., Mishra, B., Sastri, A., Aggarwal, H., Das, D., & Gupta, R. (2003). Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. *Field Crops Research*, *80*(3), 223–234. https://doi.org/10.1016/s0378-4290(02)00194-6

Pathak, H., Prasad, S., Bhatia, A., Singh, S., Kumar, S., Singh, J., & Jain, M. C. (2022). Methane emission from rice–wheat cropping system in the Indo-Gangetic plain in relation to irrigation, farmyard manure and dicyandiamide application. *Agriculture, ecosystems & environment*, *97*(1-3), 309-316.

Pazhanivelan, S., Geethalakshmi, V., Tamilmounika, R., Sudarmanian, N. S., Kaliaperumal, R., Ramalingam, K., Sivamurugan, A. P., Mrunalini, K., Yadav, M. K., & Quicho, E. D. (2022). Spatial Rice Yield Estimation Using Multiple Linear Regression Analysis, Semi-Physical Approach and Assimilating SAR Satellite Derived Products with DSSAT Crop Simulation Model. *Agronomy*, *12*(9), 2008. https://doi.org/10.3390/agronomy12092008

Penuelas, J., Baret, F., and I. Filella. (1995). Semiempirical indices to assess carotenoids/ chlorophyll –a ratio from leaf spectral reflectance. *Photosynthetica,* 31: 221–230.

Phakamas, N., Jintrawet, A., Patanothai, A., Sringam, P., & Hoogenboom, G. (2013). Estimation of solar radiation based on air temperature and application with the DSSAT v4. 5 peanut and rice simulation models in Thailand. *Agricultural and Forest Meteorology*, *180*, 182-193.

Pillai, K. G., & De, R. (1980). Growth and grain yield of rice variety Jaya at different levels and timings of nitrogen application under two systems of water management. In *Proceedings/Indian Academy of Sciences* (Vol. 89, No. 4, pp. 243-256). New Delhi: Springer India.

Ponnamperuma, F. M. (1972) The chemistry of submerged soils. Adv. Agron. 24, 2946.

Porter, J. R., Challinor, A. J., Henriksen, C. B., Howden, S. M., Martre, P., & Smith, P. (2019). Invited review: Intergovernmental Panel on Climate Change, agriculture, and food—A case of shifting cultivation and history. *Global Change Biology*, 25(8), 2518-2529.

Prasad, L. R. V., & Mailapalli, D. R. (2017). Evaluation of nitrogen fertilization patterns using DSSAT for enhancing grain yield and nitrogen use efficiency in rice. *Communications in Soil Science and Plant Analysis*, 49(12), 1401-1417.

Probert, M. E., & Dimes, J. P. (2004). Modelling release of nutrients from organic resources using APSIM. In *ACIAR PROCEEDINGS* (pp. 25-31). ACIAR; 1998.

Pruthvi, V., Narasimhan, R., & Nataraja, K. N. (2014). Simultaneous Expression of Abiotic Stress Responsive Transcription Factors, AtDREB2A, AtHB7 and AtABF3 Improves Salinity and Drought Tolerance in Peanut (Arachis hypogaea L.). *PLoS ONE*, *9*(12), e111152. https://doi.org/10.1371/journal.pone.0111152

Qi, C., Yin, X., & Xie, H. (1993). A Rice Growth Calendar Simulation Model (RICAM) and its application. *Journal of Agricultural Meteorology*, *48*(5), 831–834. https://doi.org/ 10.2480/ agrmet.48.831

Qi, H., Zhu, B., Wu, Z., Liang, Y., Li, J., Wang, L., Chen, T., Lan, Y., & Zhang, L. (2020). Estimation of Peanut Leaf Area Index from Unmanned Aerial Vehicle Multispectral Images. *Sensors*, *20*(23), 6732. https://doi.org/10.3390/s20236732

R, H. P. (2002). *A Textbook Of Soil Chemical Analysis*. http://books.google.ie/ books? id=1NACNQEACAAJ&dq=A+Textbook+of+Soil+Chemical+Analysis&hl=&cd=2&source=gbs_api

Rahman, M. M., Amano, T., & Shiraiwa, T. (2009). Nitrogen use efficiency and recovery from N fertilizer under rice-based cropping systems. *Australian Journal of Crop Science*, *3*(6), 336-351.

Raine, S. R., Meyer, W. S., Rassam, D. W., Hutson, J. L., & Cook, F. J. (2007). Soil–water and solute movement under precision irrigation: knowledge gaps for managing sustainable root zones. *Irrigation Science*, *26*, 91-100.

Raju, C., Ajith, K., Ajithkumar, B., Anitha, S., & Vijayan, V. D. (2022). Rice area mapping in Palakkad district of Kerala using Sentinel-2 data and Geographic information system technique. *Journal of Applied and Natural Science*, *14*(4), 1360–1366. https://doi.org/10.31018/jans.v14i4.3898

Ramesh, T., Sathiya, K., Padmanaban, P. K., & Martin, G. J. (2009). Optimization of nitrogen and suitable weed management practice for aerobic rice. *Madras Agricultural Journal*, *96*(2), 1.

Ramírez-Cuesta, J. M., Mirás-Avalos, J. M., Rubio-Asensio, J. S., & Intrigliolo, D. S. (2018). A novel ArcGIS toolbox for estimating crop water demands by integrating the dual crop coefficient approach with multi-satellite imagery. *Water*, *11*(1), 38.

Rao, V. R., Ramakrishnan, B., Adhya, T. K., Kanungo, P. K., & Nayak, D. N. (1998). Current status and future prospects of associative nitrogen fixation in rice. *World Journal of Microbiology and Biotechnology*, *14*, 621-633.

Rauff, K. O., & Bello, R. (2015). A review of crop growth simulation models as tools for agricultural meteorology. *Agricultural Sciences*, *6*(09), 1098.

Ray, M., Roul, P. K., & Baliarsingh, A. (2018). Application of dssat crop simulation model to estimate rice yield in Keonjhar district of Odisha (India) under changing climatic conditions. *Int. J. Curr. Microbiol. App. Sci*, *7*(4), 659-67.

Razavipour, T., Moghaddam, S. S., Doaei, S., Noorhosseini, S. A., & Damalas, C. A. (2018). Azolla (Azolla filiculoides) compost improves grain yield of rice (Oryza sativa L.) under different irrigation regimes. *Agricultural Water Management*, *209*, 1-10.

Razzaghi, F., Zhou, Z., Andersen, M. N., & Plauborg, F. (2017). Simulation of potato yield in temperate condition by the AquaCrop model. *Agricultural Water Management*, 191, 113-123.

Reddy, A. K., Prudhvi, N., & Mehta, C. M. (2020). Direct seeded rice-future of rice (Oryza sativa) cultivation. *International Journal of Research and Analytical Reviews*, *7*(4), 279-291.

Reddy, M. M., Padmaja, B., Veeranna, G., & Reddy, D. V. V. (2013). Response of aerobic rice to irrigation scheduling and nitrogen doses under drip irrigation. *Journal of Research ANGRAU*, *41*(2), 144-148.

Reddy, N. (2019). Sustainable applications of coir and other coconut by-products. Cham: Springer International Publishing.

Rezvi, H. U. A., Tahjib-Ul-Arif, M., Azim, M. A., Tumpa, T. A., Tipu, M. M. H., Najnine, F., ... & Brestič, M. (2023). Rice and food security: Climate change implications and the future prospects for nutritional security. *Food and Energy Security*, *12*(1), e430.

Riahi, K., Kriegler, E., Johnson, N., Bertram, C., den Elzen, M., Eom, J., Schaeffer, M., Edmonds, J., Isaac, M., Krey, V., Longden, T., Luderer, G., Méjean, A., McCollum, D. L., Mima,

S., Turton, H., van Vuuren, D. P., Wada, K., Bosetti, V., Capros, P., Edenhofer, O. (2015). Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, *90*, 8–23. https://doi.org/10.1016/j.techfore.2013.09.016

Richards, L. A., & Fireman, M. (1943). Pressure-plate apparatus for measuring moisture sorption and transmission by soils. *Soil Science*, *56*(6), 395-404.

Ritchie, J. T., & Otter-Nacke, S. (1985). Description and performance of CERES wheat: A user-oriented wheat yield model. *ARS wheat yield project*, 159-175.

Ritchie, J. T., Singh, U., Godwin, D. C., & Bowen, W. T. (1998). Cereal growth, development and yield. In *Understanding options for agricultural production* (pp. 79-98). Springer, Dordrecht.

Robertson, N., & Oinam, B. (2023). Rice suitability mapping using the analytic hierarchy process approach in a river catchment. *Global Journal of Environmental Science and Management*, *9*(1), 141-156.

Ros, M., Pascual, J. A., Garcia, C., Hernandez, M. T., & Insam, H. (2006). Hydrolase activities, microbial biomass and bacterial community in a soil after long-term amendment with different composts. *Soil Biology and Biochemistry*, *38*(12), 3443-3452.

Rouse, J. W., Haas, R. H., Schell, J. A., & Deering, D. W. (1973). Monitoring vegetation systems in the Great Plains with ERTS. *NASA Spece Publ*ications, *351*(1), 309.

Roy, A., Kumar, S., & Rahaman, M. (2024). Exploring climate change impacts on rural livelihoods and adaptation strategies: Reflections from marginalized communities in India. *Environmental Development*, *49*, 100937.

Roy, J., & Saha, S. (2018). Assessment of land suitability for the paddy cultivation using analytical hierarchical process (AHP): A study on Hinglo river basin, Eastern India. *Modeling Earth Systems and Environment*, *4*, 601-618.

Rugira, P., Ma, J., Zheng, L., Wu, C., & Liu, E. (2020). Application of DSSAT CERES-maize to identify the optimum irrigation management and sowing dates on improving maize yield in Northern China. *Agronomy*, *11*(04), 674.

Saaty, T. L. (1990). An Exposition of the AHP in Reply to the Paper "Remarks on the Analytic Hierarchy Process." *Management Science*, *36*(3), 259–268. https://doi.org/ 10.1287/ mnsc. 36.3.259

Saaty, T. L. (1994). Homogeneity and clustering in AHP ensures the validity of the scale. *European Journal of Operational Research*, *72*(3), 598–601. https://doi.org/10.1016/0377-2217(94)90426-x

Saaty, T. L. (1997). That is not the analytic hierarchy process: what the AHP is and what it is not. *Journal of Multi-Criteria Decision Analysis*, *6*(6), 324–335. http://dx.doi.org/ 10.1002/ (sici)1099-1360(199711)6:6<324::aid-mcda167>3.0.co;2-q

Saaty, T. L. (2001). Fundamentals of the analytic hierarchy process. *The analytic hierarchy process in natural resource and environmental decision making*, 15-35.

Sadegh Kasmaei, L., Yasrebi, J., Zarei, M., Ronaghi, A., Ghasemi, R., Saharkhiz, M. J., Ahmadabadi, Z., & Schnug, E. (2018). Influence of Plant Growth Promoting Rhizobacteria, Compost, and Biochar of Azolla on Rosemary (Rosmarinus OfficinalisL.) Growth and Some Soil Quality Indicators in a Calcareous Soil. *Communications in Soil Science and Plant Analysis*, *50*(2), 119–131. https://doi.org/10.1080/ 00103624. 2018. 1554669

Saeed, S., Makhdum, M. S. A., Anwar, S., & Yaseen, M. R. (2023). Climate Change Vulnerability, Adaptation, and Feedback Hypothesis: A Comparison of Lower-Middle, Upper-Middle, and High-Income Countries. *Sustainability*, *15*(5), 4145.

Saha, L., & Bauddh, K. (2020). Sustainable agricultural approaches for enhanced crop productivity, better soil health, and improved ecosystem services. *Ecological and Practical Applications for Sustainable Agriculture*, 1-23.

Samal, P., Babu, S. C., Mondal, B., & Mishra, S. N. (2022). The global rice agriculture towards 2050: An inter-continental perspective. *Outlook on Agriculture*, 00307270221088338.

Samarajeewa, K. B. D. P., Kojima, N., Sakagami, J. I., & Chandanie, W. A. (2005). The effect of different timing of top dressing of nitrogen application under low light intensity on the yield of rice (Oryza sativa L.). *Journal of Agronomy and Crop Science*, *191*(2), 99-105.

Samonte, S. O., Wilson, L. T., & McClung, A. M. (1998). Path Analyses of Yield and Yield-Related Traits of Fifteen Diverse Rice Genotypes. *Crop Science*, *38*(5), 1130–1136. https://doi.org/10.2135/cropsci1998.0011183x003800050004x

Santos, R. D., Boote, K. J., Sollenberger, L. E., Neves, A. L., Pereira, L. G., Scherer, C. B., & Gonçalves, L. C. (2016). Simulated optimum sowing date for forage pearl millet cultivars in multilocation trials in Brazilian semi-arid region. *Frontiers in Plant Science*, *8*, 2074.

Saseendran, S. A., Hubbard, K. G., Singh, K. K., Mendiratta, N., Rathore, L. S., & Singh, S. V. (1998). Optimum transplanting dates for rice in Kerala, India, determined using both CERES v3. 0 and ClimProb. *Agronomy Journal*, *90*(2), 185-190.

Saseendran, S. A., Singh, K. K., Rathore, L. S., Singh, S. V., & Sinha, S. K. (2000). Effects of climate change on rice production in the tropical humid climate of Kerala, India. *Climatic Change*, *44*, 495-514.

Satapathy, S. S., Swain, D. K., Pasupalak, S., & Bhadoria, P. B. S. (2015). Effect of elevated [CO2] and nutrient management on wet and dry season rice production in subtropical India. *The Crop Journal*, *3*(6), 468-480.

Saunois, M., Jackson, R. B., Bousquet, P., Poulter, B., & Canadell, J. G. (2016). The growing role of methane in anthropogenic climate change. *Environmental Research Letters*, *11*(12), 120207.

Scafaro, A. P., Fan, Y., Posch, B. C., Garcia, A., Coast, O., & Atkin, O. K. (2021). Responses of leaf respiration to heatwaves. *Plant, Cell & Environment*, *44*(7), 2090–2101. https://doi.org/10.1111/pce.14018

Scaria, R., & Vijayan, P. K. (2015). Spatio-Temporal Changes in The Cropping Pattern of Paddy Fields in Kerala State, A Geospatial Analysis on Palakkad District.

Schmid-Siegert, E., Stepushenko, O., Glauser, G., & Farmer, E. E. (2016a). Membranes as Structural Antioxidants: recycling of malondialdehyde to its source in oxidation-sensitive chloroplast fatty acids. *Journal of Biological Chemistry*, *291*(25), 13005–13013. https://doi.org/10.1074/jbc.m116.729921

Schmidt, A., John, K., Arida, G., Auge, H., Brandl, R., Horgan, F. G., Hotes, S., Marquez, L., Radermacher, N., Settele, J., Wolters, V., & Schädler, M. (2015). Effects of Residue Management on Decomposition in Irrigated Rice Fields Are Not Related to Changes in the Decomposer Community. *PLOS ONE*, *10*(7), e0134402. https://doi.org/10.1371/journal.pone.0134402

Schmidt, A., John, K., Auge, H., Brandl, R., Horgan, F. G., Settele, J., Zaitsev, A. S., Wolters, V., & Schädler, M. (2016). Compensatory mechanisms of litter decomposition under alternating moisture regimes in tropical rice fields. *Applied Soil Ecology*, *107*, 79–90. https://doi.org/10.1016/j.apsoil.2016.05.014

Shah, A. N., Tanveer, M., Rehman, A. U., Anjum, S. A., Iqbal, J., & Ahmad, R. (2017). Lodging stress in cereal—effects and management: an overview. *Environmental Science and Pollution Research*, *24*, 5222-5237.

Shanmugapriya, P., Rathika, S., Ramesh, T., & Janaki, P. (2019). Applications of remote sensing in agriculture-A Review. *International Journal of Current Microbiology and Applied. Science, 8*(01), 2270-2283.

Sharma, N., & Yadav, M. (1999). Rice. Crop yield: physiology and process [WWW Document]. *Physiol. Process.(accessed 5.11. 20) https://www. researchgate. net/publication/322075926_Sharma_NK_RP_Singh_MS_Yadav_and_KC_Singh_1999 _Fora g e_Production_in_Drylands_ of_Arid_and_Semi-arid_Regions_Scientific_ Publishers_ Ind i a_Jodhpur_ISBN_81-7233-218-1_152_p*.

Shaw, S. K., Sharma, A., Khatua, K. K., & Oliveto, G. (2023). An Integrated Approach to Evaluating Crop Water Requirements and Irrigation Schedule for Optimizing Furrow Irrigation Design Parameters in Kurnool District, India. *Water*, *15*(10), 1801.

Shrestha, J., Kandel, M., Subedi, S., & Shah, K. K. (2020). Role of nutrients in rice (Oryza sativa L.): A review. *Agrica*, *9*(1), 53-62.

Silwal, S., Bhattarai, S. P., & Midmore, D. J. (2020). Aerobic Rice with or without Strategic Irrigation in the Subtropics. *Agronomy*, *10*(11), 1831.

Singh, A. L., & Singh, P. K. (1987). Influence of Azolla management on the growth, yield of rice and soil fertility: II. N and P contents of plant and soil. *Plant and soil*, *102*, 49-54.

Singh, A., Mondal, S., & Chandra, N. (2019). Land suitability analysis based on soil properties and GIS for improving rice productivity in Bihar, India.

Singh, B. P., Ahmad, I., Sharma, V. C., & Shekhawat, G. S. (2000). Jhulsacast: a computerized forecast of potato late blight in western Uttar Pradesh. *Journal of the Indian Potato Association*, *27*(1-2), 25-34.

Singh, H., Prasad, P. V. V., Northup, B. K., Ciampitti, I. A., & Rice, C. W. (2023). Strategies for Mitigating Greenhouse Gas Emissions from Agricultural Ecosystems. In *Global Agricultural Production: Resilience to Climate Change* (pp. 409-440). Cham: Springer International Publishing.

Singh, H., Singh, K., & Hasan, B. (2007). Evaluation of CERES-rice model (V. 4.0) under temperate conditions of Kashmir valley, India. *Cereal Research Communications*, *35*(4), 1723-1732.

Singh, M. P. (2009). Rice productivity in India under variable climates. In *Country report presented at MARCO Symposium* (pp. 5-7).

Singh, R. K., Athokpam, H. S., Changteand, Z., & Singh, N. G. (2005). Integrated management of Azolla, vermicompost and urea on yield of and nutrient uptake by rice and soil fertility. *Journal of the Indian Society of Soil Science*, *53*(1), 107-110.

Singh, S. V., Sanadya, A., & Yadu, A. (2022a). Simulating the impact of climate change on rice yield using DSSAT model. *International Journal of Chemical Studies,* 8(3), 1824-1828. https://doi.org/10.22271/chemi.2020.v8.i3y.9473

Singh, T. B., Ali, A., Prasad, M., Yadav, A., Shrivastav, P., Goyal, D., & Dantu, P. K. (2020). Role of organic fertilizers in improving soil fertility. *Contaminants in agriculture: sources, impacts and management*, 61-77.

Singh, U. (1994). Nitrogen management strategies for lowland rice cropping system. In *Proceedings of the international conference on fertilizer usage in the tropics (FERTROP)*. The Malaysian Society of Soil Science.

Singh, U., Ritchie, J. T., & Godwin, D. C. (1993). *A user's guide to CERES Rice, V2. 10*. Muscle Schoals: International Fertilizer Development Center.

Singh, V. J., Bhowmick, P. K., Vinod, K. K., Krishnan, S. G., Nandakumar, S., Kumar, A., Kumar, M., Shekhawat, S., Dixit, B. K., Malik, A., Ellur, R. K., Bollinedi, H., Nagarajan, M., & Singh, A. K. (2022b). Population Structure of a Worldwide Collection of Tropical Japonica Rice Indicates Limited Geographic Differentiation and Shows Promising Genetic Variability Associated with New Plant Type. *Genes*, *13*(3), 484. https://doi.org/10.3390/genes13030484

Sistani, K. R., Jn-Baptiste, M. A. R. C. I. A., Lovanh, N., & Cook, K. L. (2011). Atmospheric emissions of nitrous oxide, methane, and carbon dioxide from different nitrogen fertilizers. *Journal of environmental quality*, *40*(6), 1797-1805.

Smith, M. (1992). *CROPWAT: A computer program for irrigation planning and management* (No. 46). Food & Agriculture Org.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N. H., Rice, C. W., Abad, C. R., Romanovskaya, A., Sperling, F., Tubiello, F. N., & Bolwig, S. (2014). Agriculture, forestry and other land use (AFOLU). In *Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 811-922). Cambridge University Press.

Smith, P., Haberl, H., Popp, A., Erb, K. H., Lauk, C., Harper, R., Tubiello,F. N., Pinto, A. S., Jafari, M., Sohi, S., Masera,O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark,H., Dong, H., Elsiddig, E. A., Mbow, C., Ravindranath, R.H., Rice, C. W., Abad, C. R., Romanovskaya, A., Sperling, F., Herrero, M., House, J. I., & Rose, S. (2013). How much land-based greenhouse gas mitigation can be achieved

without compromising food security and environmental goals?. *Global change biology*, *19*(8), 2285-2302.

Song, W., Li, J., Sun, H., Huang, S., Gong, X., Ma, Q., Zhang, Y., & Xu, G. (2013). Increased photosynthetic capacity in response to nitrate is correlated with enhanced cytokinin levels in rice cultivar with high responsiveness to nitrogen nutrients. *Plant and Soil*, *373*(1–2), 981–993. https://doi.org/10.1007/s11104-013-1867-x

Sorensen, P. O., Finzi, A. C., Giasson, M. A., Reinmann, A. B., Sanders-DeMott, R., & Templer, P. H. (2018). Winter soil freeze-thaw cycles lead to reductions in soil microbial biomass and activity not compensated for by soil warming. *Soil Biology and Biochemistry*, *116*, 39–47. https://doi.org/10.1016/j.soilbio.2017.09.026

Sowmya, C., & Ramana, M. V. (2012). Performance of Hybrids/High Yielding Varieties and Nutrient Management in System of Rice Intensification–A Review. *Agricultural Reviews*, *33*(1), 1-15.

Sravan, T., Rangare, N. R., Suresh, B. G., & Kumar, S. R. (2012). Genetic variability and character association in rainfed upland rice (Oryza sativa L.). *Journal of Rice Research*, *5*(1), 2.

Sruthi, P., & Surendran, U. (2023). Evaluation of nutrient management and method of planting on crop productivity of aerobic rice and estimating the water saving in aerobic using FAO-CROPWAT model. *Paddy and Water Environment*, 1-11.

Ssenku, J. E., Nabyonga, L., Kitalikyawe, J., Ntambi, S., Aguttu, G., & Mustafa, A. S. (2021). Potential of Azolla pinnata R. Br. green manure for boosting soil fertility and yield of terrestrial crops in Uganda: a case study of Eleusine coracana (L.) Gaertn. *Journal of Crop Science and Biotechnology*, *25*(1), 9–18. https://doi.org/10.1007/s12892-021-00108-2

Stanford, G., & English, L. (1949). Use of the Flame Photometer in Rapid Soil Tests for K and Ca. *Agronomy Journal*, *41*(9), 446–447. https://doi.org/10.2134/agronj1949.00021962004100090012x

Steduto, P., Hsiao, T. C., Raes, D., & Fereres, E. (2009). AquaCrop—The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal*, *101*(3), 426-437.

Stöckle, C. O., Donatelli, M., & Nelson, R. (2003). CropSyst, a cropping systems simulation model. *European journal of agronomy*, *18*(3-4), 289-307.

Stöckle, C. O., Kemanian, A. R., Nelson, R. L., Adam, J. C., Sommer, R., & Carlson, B. (2014). CropSyst model evolution: From field to regional to global scales and from research to decision support systems. *Environmental modelling & software*, *62*, 361-369.

Su, Y. X., Xu, H., & Yan, L. J. (2017). Support vector machine-based open crop model (SBOCM): Case of rice production in China. *Saudi journal of biological sciences,24*(3), 537-547.

Subash, N., & Mohan, H. R. (2012). Evaluation of the impact of climatic trends and variability in rice–wheat system productivity using Cropping System Model DSSAT over the Indo-Gangetic Plains of India. *Agricultural and Forest Meteorology*, *164*, 71-81.

Subbiah, B. V., & Asija, G. L. (1956). A rapid method for the estimation of nitrogen in soil. *Current Science*, *26*, 259-260.

Subedi, P., & Shrestha, J. (2015). Improving soil fertility through Azolla application in low land rice: A review.

Sudhir-Yadav, Gill, G., Humphreys, E., Kukal, S., & Walia, U. (2011). Effect of water management on dry seeded and puddled transplanted rice. Part 1: Crop performance. *Field Crops Research*, *120*(1), 112–122. https://doi.org/10.1016/j.fcr.2010.09.002

Sugathan, N., Biju, V., & Renuka, G. (2014). Influence of soil moisture content on surface albedo and soil thermal parameters at a tropical station. *Journal of earth system science*, *123*, 1115-1128.

Sui, B., Feng, X., Tian, G., Hu, X., Shen, Q., & Guo, S. (2013). Optimizing nitrogen supply increases rice yield and nitrogen use efficiency by regulating yield formation factors. *Field Crops Research*, *150*, 99-107.

Sun, Y., Ma, J., Sun, Y., Xu, H., Yang, Z., Liu, S., Jia, X., & Zheng, H. (2012). The effects of different water and nitrogen managements on yield and nitrogen use efficiency in hybrid

rice of China. *Field Crops Research*, *127*, 85–98. https://doi.org/10.1016/ j.fcr. 2011. 11.015

Surendran, U., Anagha, B., Gopinath, G., & Joseph, E. J. (2019). Long-term rainfall analysis towards detection of meteorological drought over Kozhikode District of Kerala. *Journal of Climate Change*, *5*(2), 23-34.

Surendran, U., Raja, P., Jayakumar, M., & Subramoniam, S. R. (2021). Use of efficient water saving techniques for production of rice in India under climate change scenario: A critical review. *Journal of Cleaner Production*, *309*, 127272.

Surendran, U., Rama Subramoniam, S., Raja, P., Kumar, V., & Murugappan, V. (2016). Budgeting of major nutrients and the mitigation options for nutrient mining in semi-arid tropical agro-ecosystem of Tamil Nadu, India using NUTMON model. *Environmental monitoring and assessment*, *188*(4), 1-17.

Surendran, U., Sushanth, C. M., Mammen, G., & Joseph, E. J. (2014). Modeling the impacts of increase in temperature on irrigation water requirements in Palakkad district: A case study in humid tropical Kerala. *Journal of Water and Climate Change*, *5*(3), 472-485.

Surendran, U., Sushanth, C. M., Mammen, G., & Joseph, E. J. (2015). Modelling the crop water requirement using FAO-CROPWAT and assessment of water resources for sustainable water resource management: A case study in Palakkad district of humid tropical Kerala, India. *Aquatic Procedia*, *4*, 1211-1219.

Surendran, U., Sushanth, C. M., Mammen, G., & Joseph, E. J. (2017). FAO-CROPWAT model-based estimation of crop water need and appraisal of water resources for sustainable water resource management: Pilot study for Kollam district–humid tropical region of Kerala, India. *Current Science*, 76-86.

Suryaprabha, A.C., Thiyagarajan, T. M., & Senthivelu, M. (2011). System of rice intensification principles on growth parameters, yield attributes and yields of rice (Oryza sativa L.). *Journal of Agronomy*, *10*(1), 27-33.

Swain, D. K., & Yadav, A. (2009). Simulating the Impact of Climate Change on Rice Yield Using CERES-Rice Model. *Journal of Environmental Informatics*, *13*(2).

Swain, K. C., Jayasuriya, H. P., & Salokhe, V. M. (2007). Suitability of low-altitude remote sensing images for estimating nitrogen treatment variations in rice cropping for precision agriculture adoption. *Journal of Applied Remote Sensing*, *1*(1), 013547.

Swapna, S., & Shylaraj, K. S. (2017). Screening for Osmotic Stress Responses in Rice Varieties under Drought Condition. *Rice Science*, *24*(5), 253–263. https://doi.org/10.1016/j.rsci.2017.04.004

Talley, S. N., Talley, B. J., & Rains, D. W. (1977). Nitrogen fixation by Azolla in rice fields. *Genetic engineering for nitrogen fixation*, 259-281.

Tanaka, A., & Garcia, C. V. (1965). Studies of the relationship between tillering and nitrogen uptake of the rice plant: 2. Relation between tillering and nitrogen metabolism of the plant. *Soil Science and plant nutrition*, *11*(3), 31-37.

Tang, S., Cheng, W., Hu, R., Guigue, J., Kimani, S. M., Tawaraya, K., & Xu, X. (2016). Simulating the effects of soil temperature and moisture in the off-rice season on rice straw decomposition and subsequent CH 4 production during the growth season in a paddy soil. *Biology and Fertility of Soils*, *52*, 739-748.

Tanko, U.M., & Hassan, U.T. (2016). Leaf area determination for maize (Zea mays L.), okra (Abelmoschus esculentus L.) and cowpea (Vigna unguiculata L.) crops using linear measurements. *J. Biol. Agric. Healthc*, *6*(4), 104-111.

Thakur, A. K., Rath, S., Patil, D. U., & Kumar, A. (2011). Effects on rice plant morphology and physiology of water and associated management practices of the system of rice intensification and their implications for crop performance. *Paddy and water Environment*, *9*(1), 13-24.

Thomas, J. J. (2011). Paddy cultivation in Kerala. *Review of Agrarian Studies*, *1*(2369-2021-121).

Timsina, J., & Humphreys, E. (2003). Performance and application of CERES and SWAGMAN.

Tittonell, P., Corbeels, M., Van Wijk, M. T., & Giller, K. E. (2010). FIELD—A summary simulation model of the soil–crop system to analyse long-term resource interactions and use efficiencies at farm scale. *European Journal of Agronomy*, *32*(1), 10-21.

Todorovic, M., Riezzo, E. E., Buono, V., Zippitelli, M., Galiano, A., & Cantore, V. (2016). Hydro-Tech: An automated smart-tech Decision Support Tool for eco-efficient irrigation management. *International Agricultural Engineering Journal*, *25*(2), 44-45.

Tojo Soler, C. M., Suleiman, A., Anothai, J., Flitcroft, I., & Hoogenboom, G. (2013). Scheduling irrigation with a dynamic crop growth model and determining the relation between simulated drought stress and yield for peanut. *Irrigation science*, *31*(5), 889-901.

Tripathi, R. P. (1996). Water management in rice-wheat system. *Rice-Wheat Cropping System*.

Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote sensing of Environment*, *8*(2), 127-150.

Tuong, T. P., & Bouman, B. A. (2003). Rice production in water-scarce environments. *Water productivity in agriculture: Limits and opportunities for improvement*, *1*, 13-42.

Uehara, G. (1989). Technology transfer in the tropics. *Outlook on Agriculture*, *18*(1), 38-42.

Umesh, M. R., Chittapur, B. M., & Angadi, S. (2017). Alternate wetting and drying (AWD) irrigation for rice to enhance water productivity and sustainable production: a review. *Journal of Farm Sciences*, *30*(4), 441-449.

UN DESA, 2022, https://www.un.org/development/desa/pd/content/World-Population-Prospects-2022

Ungureanu, N., Vlăduț, V., & Voicu, G. (2020). Water scarcity and wastewater reuse in crop irrigation. *Sustainability*, *12*(21), 9055.

Vano, I., Matsushima, M., Tang, C., & Inubushi, K. (2009). Effects of peat moss and sawdust compost applications on N2O emission and N leaching in blueberry cultivating soils. *Soil science and plant nutrition*, *57*(2), 348-360.

Varadan, K. M. (1996). Water module for upland crops of Kerala. *Published by CWRDM, Kozhikode*, 59.

Villalobos, F. J., Delgado, A., López-Bernal, Á., & Quemada, M. (2020). FertiliCalc: A decision support system for fertilizer management. *International Journal of Plant Production*, *14*(2), 299-308.

Voulodimos, A. S., Patrikakis, C. Z., Sideridis, A. B., Ntafis, V. A., & Xylouri, E. M. (2010). A complete farm management system based on animal identification using RFID technology. *Computers and electronics in agriculture*, *70*(2), 380-388.

VYang, Y., Watanabe, M., Zhang, X., Zhang, J., Wang, Q., & Hayashi, S. (2006). Optimizing irrigation management for wheat to reduce groundwater depletion in the piedmont region of the Taihang Mountains in the North China Plain. *Agricultural Water Management*, *82*(1–2), 25–44. https://doi.org/10.1016/j.agwat.2005.07.020

Vysakh, A., Ajithkumar, B., & Rao, A. S. (2016). Evaluation of CERES-Rice model for the selected rice varieties of Kerala. *Journal of Agrometeorology*, *18*(1), 120-123.

Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil science*, *37*(1), 29-38.

Wang, H., Wang, F., Wang, C., & Han, Y. (2019). Effects of floating Azolla on phosphorus fluxes and recovery from former agricultural lands in wetland microcosms. *Soil Science and Plant Nutrition*, *65*(1), 90-99.

Wang, N., Zhang, N., & Wang, M. (2006). Wireless sensors in agriculture and food industry—Recent development and future perspective. *Computers and electronics in agriculture*, *50*(1), 1-14.

Wang, Y., Wang, S., Sun, J., Dai, H., Zhang, B., Xiang, W., Hu, Z., Li, P., Yang, J., & Zhang, W. (2021). Nanobubbles promote nutrient utilization and plant growth in rice by upregulating nutrient uptake genes and stimulating growth hormone production. *Science of the Total Environment*, *800*, 149627. https://doi.org/10.1016/j.scitotenv.2021.149627

Wassmann, R., Nelson, G. C., Peng, S. B., Sumfleth, K., Jagadish, S. V. K., Hosen, Y., & Rosegrant, M. W. (2010). Rice and global climate change. *Rice in the global economy: strategic research and policy issues for food security*, 411-432.

Watanabe, I., Lapis, M., Oliveros, R., & Ventura, W. (1988). Improvement of phosphate fertilizer application toAzolla. *Soil Science and Plant Nutrition*, *34*(4), 557–569. https://doi.org/10.1080/00380768.1988.10416471

Wessén, B., & Berg, B. (1986). Long-term decomposition of barley straw: chemical changes and ingrowth of fungal mycelium. *Soil Biology and Biochemistry*, *18*(1), 53-59.

Widodo, T. W., & Muhklisin, I. (2022). Effect of Soilless Media with Alternate Wetting-Drying (AWD) as Basic Irrigation on the Growth of Two Varieties of Rice. In *IOP Conference Series: Earth and Environmental Science* (Vol. 980, No. 1, p. 012054). IOP Publishing.

Widyastuti, R. (2003). Soil Fauna in Rainfed Paddy Field Ecosystems. Cuvillier Verlag. http://books.google.ie/books?id=-YsAAgAACAAJ&dq=Widyastuti,+R.+(2002).+Soil+fauna+in+rainfed+paddy+field+ecoystems:+their+role+in+organic+matter+decomposition+and+nitrogen+mineralization&hl=&cd=1&source=gbs_api

Wiegand, C. L., & Richardson, A. J. (1984). Leaf Area, Light Interception, and Yield Estimates from Spectral Components Analysis 1. *Agronomy Journal*, *76*(4), 543-548.

Williams, J. R. (1990). The erosion-productivity impact calculator (EPIC) model: a case history. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *329*(1255), 421-428.

Williams, R. L., Durkin, C. O., & Stapper, M. (1994). A simple model of rice yield response to N fertiliser and its use in a decision support system.

Win, E. P., Win, K. K., Bellingrath-Kimura, S. D., & Oo, A. Z. (2020). Greenhouse gas emissions, grain yield and water productivity: a paddy rice field case study based in Myanmar. *Greenhouse Gases: Science and Technology*, *10*(5), 884-897.

WMO, 2008. Guide to meteorological instruments and methods of observation. 7th ed. WMO Instruments and Observing Methods Rep. WMO-8: 681.

Wopereis, M. C. S., Kropff, M. J., Maligaya, A. R., & Tuong, T. P. (1996). Drought-stress responses of two lowland rice cultivars to soil water status. *Field Crops Research*, *46*(1-3), 21-39.

Wu, D., Yu, Q., Lu, C., & Hengsdijk, H. (2006). Quantifying production potentials of winter wheat in the North China Plain. *European Journal of Agronomy*, *24*(3), 226-235.

Wu, D., Yu, Q., Wang, E., & Hengsdijk, H. (2008). Impact of spatial-temporal variations of climatic variables on summer maize yield in North China Plain. *International Journal of Plant Production*. https://doi.org/10.1016/j.jag.2021.102668

Wu, K., Wang, S., Song, W., Zhang, J., Wang, Y., Liu, Q., Yu, J., Ye, Y., Li, S., Chen, J., Zhao, Y., Wang, J., Wu, X., Wang, M., Zhang, Y., Liu, B., Wu, Y., Harberd, N. P., & Fu, X. (2020). Enhanced sustainable green revolution yield via nitrogen-responsive chromatin modulation in rice. *Science*, *367*(6478). https://doi.org/10.1126/science.aaz2046

Wu, W. (2014). The Generalized Difference Vegetation Index (GDVI) for Dryland Characterization. *Remote Sensing*, *6*(2), 1211–1233. https://doi.org/10.3390/rs6021211

Xiao, X., Boles, S., Liu, J., Zhuang, D., Frolking, S., Li, C., Salas, W., & Moore, B. (2005). Mapping paddy rice agriculture in southern China using multi-temporal MODIS images. *Remote Sensing of Environment*, *95*(4), 480–492. https://doi.org/ 10.1016 /j.rse. 2004. 12.009

Yadvinder-Singh, Bijay-Singh, Ladha, J. K., Khind, C. S., Khera, T. S., & Bueno, C. S. (2004). Effects of Residue Decomposition on Productivity and Soil Fertility in Rice–Wheat Rotation. *Soil Science Society of America Journal*, *68*(3), 854–864. https://doi.org/10.2136/sssaj2004.8540

Yang, D., Cai, T., Luo, Y., & Wang, Z. (2019). Optimizing plant density and nitrogen application to manipulate tiller growth and increase grain yield and nitrogen-use efficiency in winter wheat. *PeerJ*, *7*, e6484. https://doi.org/10.7717/peerj.6484

Yang, G., Tang, H., Nie, Y., & Zhang, X. (2011). Responses of cotton growth, yield, and biomass to nitrogen split application ratio. *European Journal of Agronomy*, *35*(3), 164–170. https://doi.org/10.1016/j.eja.2011.06.001

Yang, J. M., Yang, J. Y., Dou, S., Yang, X. M., & Hoogenboom, G. (2013). Simulating the effect of long-term fertilization on maize yield and soil C/N dynamics in northeastern China using DSSAT and CENTURY-based soil model. *Nutrient Cycling in Agroecosystems*, *95*(3), 287–303. https://doi.org/10.1007/s10705-013-9563-z

Yang, J., Zhou, Q., & Zhang, J. (2017). Moderate wetting and drying increases rice yield and reduces water use, grain arsenic level, and methane emission. *The Crop Journal*, *5*(2), 151–158. https://doi.org/10.1016/j.cj.2016.06.002

Yao, F., Huang, J., Cui, K., Nie, L., Xiang, J., Liu, X., Wu, W., Chen, M., & Peng, S. (2012). Agronomic performance of high-yielding rice variety grown under alternate wetting and drying irrigation. *Field Crops Research*, *126*, 16–22. https://doi.org/10.1016/ j.fcr. 2011. 09.018

Yao, Y., Zhang, M., Tian, Y., Zhao, M., Zeng, K., Zhang, B., Zhao, M., & Yin, B. (2018). Azolla biofertilizer for improving low nitrogen use efficiency in an intensive rice cropping system. *Field Crops Research*, *216*, 158–164. https://doi.org/10.1016/j.fcr.2017.11.020

Yin, X., & Qi, C. (1994). Studies on the rice growth calendar model (RICAM) and its application. *Acta Agroomica Sin*ica, *20*, 339-346.

Yin, X., & Struik, P. C. (2017). Can increased leaf photosynthesis be converted into higher crop mass production? A simulation study for rice using the crop model GECROS. *Journal of Experimental Botany*, *68*(9), 2345–2360. https://doi.org/10.1093/jxb/erx085

Yohannes, D. F., Ritsema, C., Eyasu, Y., Solomon, H., van Dam, J., Froebrich, J., Ritzema, H., & Meressa, A. (2019). A participatory and practical irrigation scheduling in semiarid areas: the case of Gumselassa irrigation scheme in Northern Ethiopia. *Agricultural Water Management*, *218*, 102–114. https://doi.org/10.1016/j.agwat.2019.03.036

Yoshida, S. (1981). *Fundamentals of rice crop science*. Int. Rice Res. Inst.

Yuan, S., Peng, S., & Li, T. (2017). Evaluation and application of the ORYZA rice model under different crop managements with high-yielding rice cultivars in central China. *Field Crops Research*, *212*, 115–125. https://doi.org/10.1016/j.fcr.2017.07.010

Zaman, N. K., Abdullah, M. Y., Othman, S., & Zaman, N. K. (2018). Growth and physiological performance of aerobic and lowland rice as affected by water stress at selected growth stages. *Rice Science*, *25*(2), 82-93.

Zaman, U., Ahmad, Z., Farooq, M., Saeed, S., Ahmad, M., & Wakeel, A. (2015). Potassium fertilization may improve stem strength and yield of Basmati rice grown on nitrogen-fertilized soils. *Pakistan Journal of Agricultural Sciences*, *52*(2).

Zhang, F., & Zhou, G. (2015). Estimation of canopy water content by means of hyperspectral indices based on drought stress gradient experiments of maize in the north plain China. *Remote Sensing*, *7*(11), 15203-15223.

Zhang, F., Cui, Z., Fan, M., Zhang, W., Chen, X., & Jiang, R. (2011). Integrated Soil-Crop System Management: Reducing Environmental Risk while Increasing Crop Productivity and Improving Nutrient Use Efficiency in China. *Journal of Environmental Quality*, *40*(4), 1051–1057. https://doi.org/10.2134/jeq2010.0292

Zhang, H., Chen, J., Ni, Y., Zhang, Q., & Zhao, L. (2009). Uptake by roots and translocation to shoots of polychlorinated dibenzo-p-dioxins and dibenzofurans in typical crop plants. *Chemosphere*, *76*(6), 740-746.

Zhang, J., Balkovič, J., Azevedo, L. B., Skalský, R., Bouwman, A. F., Xu, G., Wang, J., Xu, M., & Yu, C. (2018). Analyzing and modelling the effect of long-term fertilizer management on crop yield and soil organic carbon in China. *Science of the Total Environment*, *627*, 361–372. https://doi.org/10.1016/j.scitotenv.2018.01.090

Zhang, J., Zhang, Y. Y., Song, N. Y., Chen, Q. L., Sun, H. Z., Peng, T., Huang, S., & Zhao, Q. Z. (2021). Response of grain-filling rate and grain quality of mid-season indica rice to nitrogen application. *Journal of Integrative Agriculture*, *20*(6), 1465–1473. https://doi.org/10.1016/s2095-3119(20)63311-1

Zhang, K., Ge, X., Shen, P., Li, W., Liu, X., Cao, Q., Zhu, Y., Cao, W., & Tian, Y. (2019). Predicting Rice Grain Yield Based on Dynamic Changes in Vegetation Indexes during Early to Mid-Growth Stages. *Remote Sensing*, *11*(4), 387. https://doi.org/ 10.3390/ rs11040387

Zhang, L., Lu, Z., Velarde, L., Fu, L., Pu, Y., Ding, S. Y., Ragauskas, A. J., Wang, H. F., & Yang, B. (2015). Vibrational spectral signatures of crystalline cellulose using high resolution broadband sum frequency generation vibrational spectroscopy (HR-BB-SFG-VS). *Cellulose*, *22*(3), 1469–1484. https://doi.org/10.1007/s10570-015-0588-0

Zhang, S., Rasool, G., Guo, X., Sen, L., & Cao, K. (2020). Effects of Different Irrigation Methods on Environmental Factors, Rice Production, and Water Use Efficiency. *Water*, *12*(8), 2239. https://doi.org/10.3390/w12082239

Zhang, Y., Hou, W., Chi, M., Sun, Y., An, J., Yu, N., & Zou, H. (2020b). Simulating the effects of soil temperature and soil moisture on CO2 and CH4 emissions in rice straw-enriched paddy soil. *CATENA*, *194*, 104677. https://doi.org/10.1016/j.catena.2020.104677

Zhang, Y., Tang, Q., Peng, S., Xing, D., Qin, J., Laza, R. C., & Punzalan, B. R. (2012). Water Use Efficiency and Physiological Response of Rice Cultivars under Alternate Wetting and Drying Conditions. *The Scientific World Journal*, *2012*, 1–10. https://doi.org/ 10.1100 / 2012/ 287907

Zhang, Z., Chu, G., Liu, L., Wang, Z., Wang, X., Zhang, H., Yang, J., & Zhang, J. (2013). Mid-season nitrogen application strategies for rice varieties differing in panicle size. *Field Crops Research*, *150*, 9–18. https://doi.org/10.1016/j.fcr.2013.06.002

Zhang, Z., Li, Y., Chen, X., Wang, Y., Niu, B., Liu, D. L., He, J., Pulatov, B., Hassan, I., & Meng, Q. (2023). Impact of climate change and planting date shifts on growth and yields of double cropping rice in southeastern China in future. *Agricultural Systems*, *205*, 103581. https://doi.org/10.1016/j.agsy.2022.103581

Zhao, Z., Sha, Z., Liu, Y., Wu, S., Zhang, H., Li, C., Zhao, Q., & Cao, L. (2016). Modeling the impacts of alternative fertilization methods on nitrogen loading in rice production in Shanghai. *Science of the Total Environment*, *566–567*, 1595–1603. https://doi.org/ 10.1016/ j.scitotenv.2016.06.055

Zhu, G., Chen, Y., Ella, E. S., & Ismail, A. M. (2018). Mechanisms associated with tiller suppression under stagnant flooding in rice. *Journal of Agronomy and Crop Science*, *205*(2), 235–247. https://doi.org/10.1111/jac.12316

Appendices

Paper published in peer reviewed journal

* **Sruthi, P**., & Surendran, U. (2023). Evaluation of nutrient management and method of planting on crop productivity of aerobic rice and estimating the water saving in aerobic using FAO-CROPWAT model. *Paddy and Water Environment*, 1-11. https://doi.org/10.1007/s10333-023-00941-x

Papers presented in conference

* **P. Sruthi** and U. Surendran. Evaluating the Impact of Different Management Strategies for Rice *(cv. Uma)* under Aerobic System. International conference on Climate Resilient Agriculture for Sustainable Agriculture Productivity held during **31st March, 2023** Organized by Mother Terasa College of Agriculture, Tamil Nadu.
* **P. Sruthi**, U Surendran, and C. T. Muhamed Fasil. Assessing the influence of different organic management practices on paddy yield. International Conference on Water and Environmental Management (WEM-2022), 22-24 June, **2022**, CWRDM, Kozhikode, Kerala.
* **P. Sruthi,** U. Surendran, Ashish K. Chaturvedi and K Madhava Chandran. Assessing the influence of nutrient management and method of irrigation on two different rice cultivars. III Indian National Ground Water Conference, 18-20 February, 2020, CWRDM, Kozhikode, Kerala.

Poster Presentation

* **P. Sruthi** and U. Surendran. Evaluating the influence of nutrient management and irrigation method on growth of two different rice cultivars - Uma and Kanchana, International Web-Conference on Resource Management and Biodiversity Conservation to Achieve Sustainable Development Goals, ANRCM, Lucknow, UP, India organized online on September 11-12, 2020.
* **P. Sruthi** and U. Surendran. Soil health assessment- Post flood Scenario in humid tropical Kerala. International conference on Climate Resilient Agriculture for Sustainable Agriculture Productivity held during 31st March, 2023 Organized by Mother Terasa College of Agriculture, Tamil Nadu.

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ARTICLE

Evaluation of nutrient management and method of planting on crop productivity of aerobic rice and estimating the water saving in aerobic using FAO-CROPWAT model

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Abstract
Rice is one of the most important cereal crops and is a prime target for water conservation because it is the most widely grown crop under flood irrigation. Rapidly depleting water resources threaten the sustainability of the irrigated rice production, the livelihood of rice producers and consumers, and ultimately the food security. By considering this, a field experiment was conducted with aerobic rice by evaluating different methods of planting and nutrient management practices. Treatment details are as follows: (A) method of planting, such as transplanted and direct line sowing, and (B) different nutrient management regimes (viz., T_1–125% application of inorganic fertilizers; T_2–100% application of inorganic fertilizers; and T_3–100% application of organic manures). Results showed that, among the methods of planting, direct line sowing performed better in terms of plant growth and yield parameters. With respect to nutrient management, 125% of recommended dose of inorganic N fertilizers produced a higher yield compared to other treatments, and the difference was statistically significant. Organic manure applied as a treatment produced the lowest crop growth parameters and yield. Furthermore, water requirements for aerobic and anaerobic rice were compared using FAO-CROPWAT, and results revealed a 36.4% water saving.

Keywords Aerobic rice · CROPWAT · Yield · Anaerobic rice · Water saving

Introduction

Rice (*Oryza sativa* L.) was cultivated 7000 years ago in the Assam–Meghalaya areas of India and in the mountain regions of Southeast Asia and Southwest China. Nearly 90% of the world's rice is produced and consumed in Asia, which accounts for nine of the top ten rice-producing countries across the globe (Prasad 2011). Globally, India ranks first in rice area and second in rice production after China (Mondal et al. 2020; Shekhawat et al. 2020). India is the largest rice-growing country in the world with a 43 million ha area or nearly 27% of India's total 159 million hectares of arable land; rice is the staple food grain for half of the country's population, and it grows in all states and agroclimatic zones (Shah et al. 2021). As a result, it is one of the essential crops for food security, with agriculture providing income to around 59% of the Indian population. However, in terms of total production, India is second in the world with 152.6 million tonnes, the first being China with 206.09 million tonnes. This anomaly is due to the per hectare low productivity of rice in India (3590 kg/ha) compared to China (6740 kg/ha) (Surendran et al. 2021). The lower rice yields below the national average in 348 districts of the country contribute to the overall low productivity of rice in India.

Rice is not an obligate aquatic plant; it does have a physiological mechanism that allows it to withstand flooding by producing aerenchyma. Aerenchyma is air passages that facilitate gas exchange between the environment and the rhizosphere, allowing active nutrient uptake and root development to occur (Yoshida 1981) even in the case of flooding/saturation. Flooding paddies provide several advantages, including acting as a physical weed control method, increasing nutrient availability by desorption of nutrients from soil colloids, and assisting in the maintenance of a soil pH equilibrium close to neutral. Floodwater also acts as thermal insulation, allowing temperature extremes to be moderated, which is especially crucial during microsporogenesis.

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During the growing season, rice requires approximately 5500 m^3 ha^{-1}–11,200 m^3 ha^{-1} of water, depending on the soil and tillage method (de Avila et al. 2015; Surendran et al. 2021).

Although, the conventional flooding system is highly productive and restrict weed growth, it demands a huge quantity of water (Hafeez-ur-Rehman et al. 2019; Bhatt et al. 2019). However, coping with the impact of climate change on agriculture will require careful management of all the natural resources such as water, soil, and biodiversity. To cope with the impact of climate change on agriculture and food production, India will need to act at the global, regional, national, and local levels to ensure the food security. Globally, India is the largest groundwater user (230 km^3 yr^1), accounting for more than a quarter of all worldwide water use (Surendran et al. 2021). Rather than being a big water consumer, the agricultural sector appears to be losing ground since water allotted for irrigation is expected to diminish in the future years (Bhatt et al. 2016). Water availability per capita is already declining in Asia's key rice-growing countries. Irrigation is a basic requirement for agriculture, but its injudicious use leads in excessive consumption of the green and blue water required for this industry (Bhatt et al. 2016). Hence, rice is a prime target for water conservation because it is the most widely grown crop under irrigation. About 55% of the rice area is irrigated and accounts for 75% of the total rice production in the world. Rice accounts for 34–43% of the world's irrigation water (Arbat et al. 2020). In Asia, more than 80% of the developed freshwater resources used for irrigation purposes, out of which more than 50% used for irrigating rice. Rapidly depleting water resources threaten the sustainability of the irrigated rice and hence the food security and livelihood of rice producers and consumers. Conventional rice production systems (puddled transplanting) require large quantities of water. Farmers have to use 2–3 times more water in rice fields than in fields for other cereals to produce 1 kg of grain; on average, 2500 L of water are used to create 1 kg of rice grain (Bouman et al. 2007; Dhillon 2022).

A number of irrigation strategies have been tested in rice systems to reduce water usage, including direct-seeded rice (DSR), aerobic rice, system of rice intensification (SRI), and alternate wetting and drying (AWD). Direct-seeded rice (DSR) is a system of rice growing in which rice seeds are sown directly in fields without going through a nursery stage or being transplanted. Direct-seeded rice (DSR) is also an attractive option among water-saving techniques and is practiced in various parts of the globe (Farooq et al. 2022). However, in light textured soils, using DSR has not been successful due to more water inputs and fluctuation of nutrient supply (Chakraborty et al. 2017). A special irrigation strategy called aerobic rice involves growing specially adapted, input-response rice varieties with aerobic adaptation in well-drained, non-puddled, and non-saturated soils with no ponded water (flooded fields), similar to the conditions that are used for growing other cereals such as wheat and maize (Bouman et al. 2007; Borja et al. 2018; Surendran et al. 2021). Direct seeding or line sowing in rice has been advocated instead of puddled transplanting in Asian countries because of non-availability of labor, shortage of irrigation water, and reduction in field expenditure, etc.

The main driving force behind aerobic rice is economic water use. Instead of trying to reduce water input in lowland paddy fields, the concept of having the field flooded or saturated is abandoned altogether. The aerobic rice technology eliminates puddling and flooding and presents an alternative system for reducing water use and increasing water productivity. In crux, aerobic rice is an attractive alternative option to the traditional rice production system. The yield penalty and yield stability of aerobic rice have to be considered before promoting this water-saving technology. Depleting groundwater level as a result of excessive use for irrigation is a major problem particularly in South Asia such as northern China, India, and Bangladesh (Surendran et al. 2021), and water-saving technologies, including aerobic rice, are being developed by researchers without considerable loss in grain yield.

Besides, continuous cultivation of rice and often under poor soil and crop management practices results in the loss of soil fertility that indicates multi-nutrient deficiencies (Dwivedi et al. 2003). Recently, the state of Kerala began to support organic farming, so that must also be considered while evaluating aerobic rice, and how this will perform under different nutrient management strategies. The current mode of water-saving irrigation emphasizes the advanced technology, but the lack of research on the risk of reduced yield has affected the scientific selection of irrigation and drainage modes. While some studies have shown that high productivity can be achieved while saving water, these practices need adequate information, which usually the policymakers and farmers lack. Some indices, such as soil moisture content, soil suction, and other parameters, are not well controlled, especially the judgment of the lower limit of irrigation is insufficient, and there is a specific amount of risk of yield reduction. This is critical since moisture content falls below the lower limit during a physiologically important stage, such as panicle initiation or grain filling, and detection is delayed; then, it will have a definite impact on the yield of rice. Hence, climate change—mitigation and adaptation options in agriculture entails taking the right measures to reduce the negative effects of climate change (or exploit the positive ones) by making the appropriate adjustments and changes in water and nutrient management strategies.

The FAO suggests the Penman–Monteith equation for computing crop water requirements because it fits well in most of the climatic regions of the globe and has

a dependable physical basis. CROPWAT 8.0 is a decision support system (DSS) developed by the FAO's Land and Water Development Division that calculates crop water requirements and total agricultural water requirements. All calculation procedures are based on two FAO publications (Doorenbos and Kassam 1979; Allen et al. 1998). The FAO-developed CROPWAT model is based on a water balance model in which soil moisture status is determined daily based on calculated evapotranspiration, rainfall, and irrigation inputs. Many studies used the FAO-CROPWAT 8.0 model to estimate reference evapotranspiration (ETo) and net irrigation water requirements (NIR) for major cultivated crops and discovered water savings of up to 44% compared to conventional methods (Surendran et al. 2015; Gabr and Fattouh 2021; Gabr 2022; Mohamed Saber et al. 2022). These studies assist farmers and other stakeholders in determining the best crop pattern for maximum income and implementing accurate irrigation schedules.

By considering the importance of water and nutrient management in rice, the present investigation was carried out to understand the influence of organic and inorganic fertilizers on the productivity of transplanted and direct planted aerobic rice and also to calculate the percentage water saving with the help of the FAO-CROPWAT 8.0 model if aerobic rice is implemented on a large scale, in the state of Kerala, India.

Materials and methods

In general, there are three different rice-growing seasons in Kerala, India, *namely, Virippu, Mundakan,* and *Puncha*. *Virippu* (autumn) is the first crop season, starting from April–May to Sept–Oct. *Mundakan* (winter) is the second crop, starting from Sept–Oct to Dec–Jan. The third crop is *Puncha* starting from Dec–Jan to March–April. This experiment was conducted during *the Virippu* season of 2019 on transplanted and direct planted aerobic rice with *the Uma variety* as the cultivar in the field of the Land and Water Management Research Group at the Centre for Water Resources Development and Management (CWRDM), Kozhikode, Kerala, India (Fig. 1). Paddy seeds were procured from the Regional Agriculture Research Station, Kerala Agricultural University in Pattambi, Kerala. The selected variety is Uma

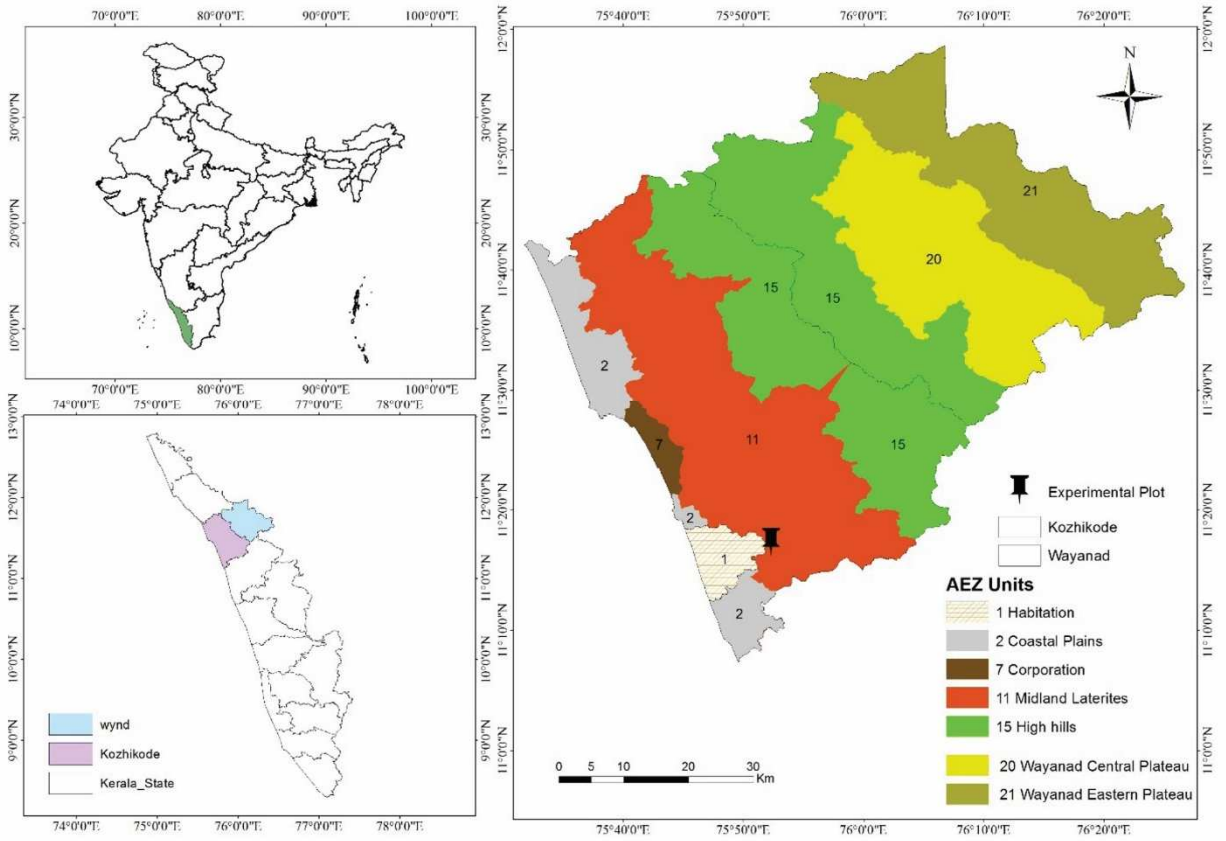

Fig. 1 Map of experimental location—CWRDM, Kozhikode, and the districts selected for the simulation study, Kerala, India

(MO16), which is a popular variety grown in Kerala and is a medium duration crop that completes its life cycle within 120–135 days during the *Virippu* season. Before the land preparation activities, soil samples were drawn from the field and analyzed for their physical–chemical properties using standard procedures (Table 1). The treatments that were attempted are as follows: (1) method of planting, which consists of (a) direct-seeded rice (DSR), a system of rice growing in which rice seeds are sown directly in fields *without going through a nursery stage or being transplanted* and (b) transplanting; and (2) nutrient management practice treatment, which consists of applying (a) 125% of the recommended dose of nutrients through inorganic fertilizers (T1), (b) 100% of the recommended dose of nutrients through inorganic fertilizers (T2), and (c) 100% of the recommended dose of nutrients through organic manure (T3). The seed rate used for both direct planting and transplanting was 80 kg ha^{-1}. In the case of DSR, line sowing was carried out with a spacing of 20 cm × 15 cm. In the case of transplanting, 25-day-old seedlings were transplanted with a spacing of 20 cm × 15 cm in the experimental plots. The recommended dose of fertilizers (NPK) was applied (KAU 2016) to each treatment. All the local cultural and management practices were adopted as per the package of practices of the Kerala Agricultural University (KAU). For organic manure, slight adjustments were made concerning phosphorus (P) and potassium (K) so that nitrogen (N) application was common as per the treatments. The dosage was applied in three stages, 1/3% of the dose at bed preparation, 1/3% of the dose of N at the maximum tillering stage, and the remaining 1/3% the of dose at the panicle initiation stage, as per the package of practices recommendations of Kerala Agricultural University (KAU 2016).

Irrigation requirement

Irrigation quantity was calculated using the FAO Penman–Monteith method (Doorenbos and Kassam 1979; Allen et al. 1998; Surendran et al. 2015; 2017) by determining reference crop evapotranspiration (ET_0), as shown in Eq. (1).

$$\mathrm{ETo} = \frac{0.408\Delta(\mathrm{R}n - G) + \Upsilon\frac{900}{T+273}u_2\left(e_s - e_s\right)}{\Delta + \Upsilon\left(1 + 0.34u_2\right)} \quad (1)$$

ET_o—Reference crop evapotranspiration (mm day^{-1}), Rn—Net radiation at the crop surface (MJ m^{-2} day^{-1}), G—Soil heat flex density (MJ m^{-2} day^{-1}), T—Mean daily air temperature at 2-m height (°C), u_2—Wind speed at 2-m height (ms^{-1}), e_s—Saturation vapor pressure (Kpa), e_a—Actual vapor pressure, e_s–e_a—Saturation vapor pressure deficit (Kpa), Δ—Slope vapor pressure curve [Kpa (°C)], and γ—Psychrometric constant [Kpa (°C)].

Irrigation requirements and the schedule were prepared for three different rice seasons in Kerala using FAO-CROPWAT software for both aerobic and anaerobic cultivation methods. The climatic variables used for the calculation of ET_o are temperature (maximum and minimum in °C), relative humidity (maximum and minimum in %), wind speed (km/day), sunshine hours/solar radiation, and latitude, longitude, and altitude collected from the meteorological observatory of CWRDM. ET_0 was calculated for every decade (i.e., 10 days) during the experimental period using long-term historic climatic data (1983–2019). Data observed during the crop growing period is given in supplementary table 1. Crop evapotranspiration (ETc) per decade is calculated by multiplying ET_0 by the crop coefficient values (K_c) taken from available published data (Surendran et al. 2017). The total water requirement was calculated as per Eq. 2.

$$\mathrm{WR} = \mathrm{ET_c} + \text{Application Lossess} + \text{Special Needs} \quad (2)$$

Table 1 Standard procedures for soil analysis

Soil properties	Method employed
Chemical properties	
Soil pH	Potentiometric method (Jackson 1967)
Organic carbon (%)	Chromic acid wet digestion (Walkley and Black, 1934)
Available nitrogen (kg ha^{-1})	Alkaline permanganate method (Subbiah and Asija 1956)
Available phosphorus (kg ha^{-1})	Olsen method (Olsen 1954)
Available potassium (kg ha^{-1})	NN NH_4OAc extraction (Hanway and Heidal, 1952)
Physical properties	
Bulk density	Interparticulate void volume (Day 1965)
Particle density	Mass to its hydrodynamic volume (Day 1965)
Soil texture	Hydrometer (Day 1965)
Field capacity and wilting point	Pressure plate apparatus (Day 1965)

where WR—Water requirement of crops, ETc—Crop evapotranspiration, and special needs—Land preparation activities for paddy

For anaerobic and aerobic rice, percolation water losses were assigned as 6 mm/day and 2 mm/day, respectively (Surendran et al. 2017). Additionally, the amount of water used for the land preparation activities for anaerobic and aerobic rice, respectively, 300 mm and 200 mm were also taken into account. Net irrigation demand or net irrigation requirement (NIR) was computed as per Eq. (3) based on the amount of crop water requirement subtracted from the effective rainfall that was received during the crop growth period and the contribution from groundwater, if any.

$$\mathrm{NIR} = \mathrm{WR} - \mathrm{ER} - Ge \tag{3}$$

where ER—Effective rainfall and *Ge*—Groundwater contribution from water table (not considered in the calculation as this is negligible).

Effective rainfall/ER (P_{eff}) is defined as the portion of the rainfall that is effectively used by the crop. After rainfall, some amount of water is lost in the form of surface runoff and deep percolation. Hence, to account for losses due to runoff or percolation, there are four methods provided in CROPWAT 8.0, namely, fixed percentage, dependable rain, empirical formula, and the USDA Soil Conservation Service methods. For this study, the USDA Soil Conservation Service method was selected.

$$P_{\mathrm{eff}} = P_{\mathrm{month}} \times \left(125 - 0.2 \times P_{\mathrm{month}}\right)/125 \text{ for } P_{\mathrm{month}} \leq 250m$$

$$P_{\mathrm{eff}} = 125 + 0.1 \times P_{\mathrm{month}} \text{for } P_{\mathrm{month}} > 250m$$

where

P_{month} = Monthly rainfall and P_{eff} = Effective rainfall.

The soils of the experimental fields were analyzed for their physicochemical properties by adopting standard procedures (Table 1). Biometric observations such as plant height, and the number of tillers, were carried out at four different stages, namely, tillering stage (30$^{\mathrm{th}}$ day), flowering stage (50$^{\mathrm{th}}$ day), maturity stage (85$^{\mathrm{th}}$ day), and harvest stage (115$^{\mathrm{th}}$ days) after planting to final harvest. The height of the plant was measured and expressed in centimeters. The height was measured from the collar region to the tip of the unfolded leaf. The total number of tillers was counted from the base and expressed as numbers. Grain measurements were measured after oven drying at 70 °C until constant weight is obtained. During sampling, the whole plant was uprooted and separated into different parts, viz., leaves, stem, and root, and biometric observations were taken. The separated samples were dried at 65 ± 4^{0} C in a hot air oven. Total biomass production was computed on a hectare basis and expressed in kg ha^{-1} at each stage (Barnaby et al. 2022) and computed using the standard procedure. Statistical analysis such as ANNOVA and post hoc (LSD) was accomplished using average values, and standard error using GRAPES software (Gopinath et al. 2021).

Simulating the water saving of aerobic rice

A simulation study was conducted to project the impact of water saving by the aerobic rice cultivation method over conventional flood irrigation (anaerobic). Two districts, viz., Kozhikode and Wayanad districts of Kerala, India, were selected for this analysis. Data sets about rice cultivation, viz., the total area of paddy cultivation, paddy production, etc., of these two districts for the past 30 years were compiled from the Department of Economics and Statistics data (DoES 2022). Based on the area of rice cultivation, the total water requirement was calculated using FAO-CROPWAT model 8.0 for both aerobic (962 mm) and flooded (1582 mm) conditions as described earlier (Surendran et al. 2017). These data were compared for water saving by assuming that the portion of the flooded area is converted into an aerobic method of cultivation.

Results and discussion

Experimental soil and site characteristics

The climate of the experimental site is humid tropical with hot dry summers and cold winter seasons. The total annual rainfall received during the year was 3351.6 mm, and nearly 80% of the rainfall was received during the southwest monsoon season from May to September, which is the experimental period (Fig. 2). In general, the experimental soil is sandy clay loam in texture with a bulk density of 1.01 g cc^{-1} and particle density of 2.06 g cc^{-1}. The soil is lateritic and taxonomically belongs to the Kunnamangalam series with the USDA class of *Mixed; Isohyperthermic, Typic Kanhaplustults*. Besides, the soil is acidic in nature with a pH of 5.93, high in organic carbon at 1.72%, low in available N of 255 kg ha^{-1}, medium in available P (20.31 kg ha^{-1}), and medium in available K of 130.6 kg ha^{-1}, respectively. The field capacity and wilting point of the experimental plot are 24.12% and 15.26%, respectively.

Biometric characteristics

Crop biometrics consisting of the number of tillers and plant height in cm is summarized in Table 2. Results showed that the aerobic rice showed statistically significant differences among the different treatments attempted.

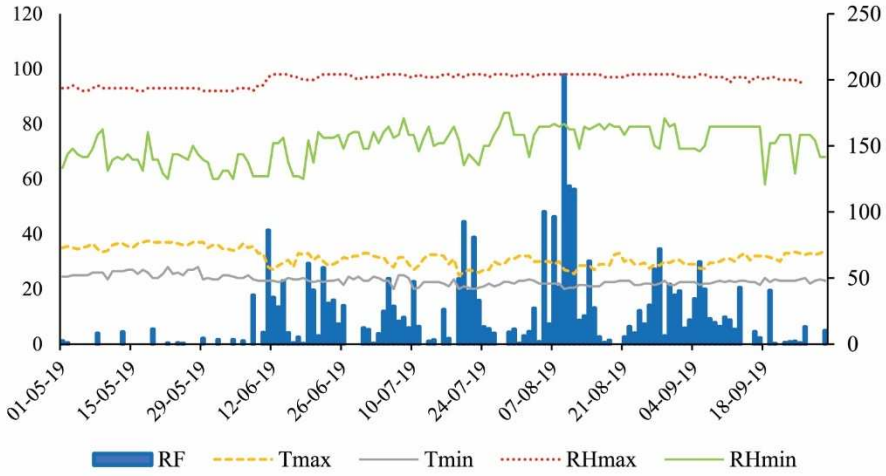

Fig. 2 Weather data during the experimental period

Table 2 Growth characteristics such as number of tillers and height of rice plant *cv Uma is represented as mean ± standard deviation (SD) of six replications*

Method	Treatment	30th Day		50th Day		85th Day		115th Day	
		Number of tillers	Height of plant (cm)	Number of tillers	Height of plant (cm)	Number of tillers	Height of plant (cm)	Number of tillers	Height of plant (cm)
Direct planted	T1	13.00 ± 1.52^{a}	36.20 ± 1.30^{a}	17.00 ± 1.00^{a}	76.60 ± 12.08^{a}	19.40 ± 0.55^{a}	85.02 ± 2.24^{a}	19.38 ± 1.12^{a}	87.5 ± 1.95^{a}
	T2	11.00 ± 1.82^{b}	34.40 ± 1.14^{ab}	15.40 ± 0.55^{b}	69.60 ± 1.14^{b}	17.20 ± 2.83^{ab}	77.60 ± 1.34^{b}	17.14 ± 1.13^{b}	82.51 ± 2.60^{b}
	T3	8.00 ± 0.71^{cd}	25.40 ± 1.32^{c}	11.60 ± 0.58^{ed}	54.20 ± 2.86^{e}	14.40 ± 0.55^{c}	66.05 ± 2.26^{e}	14.08 ± 0.19^{d}	67.14 ± 1.69^{e}
Trans-planted	T1	8.20 ± 0.84^{c}	31.80 ± 1.30^{b}	14.00 ± 0.89^{c}	66.46 ± 2.79^{c}	17.03 ± 1.00^{ab}	75.07 ± 0.89^{c}	$16.81 \pm .49^{c}$	76.06 ± 1.92^{c}
	T2	7.00 ± 1.23^{d}	26.40 ± 1.32^{c}	12.00 ± 1.41^{d}	60.03 ± 2.45^{d}	16.60 ± 0.55^{b}	73.85 ± 1.03^{d}	15.41 ± 1.05^{c}	72.94 ± 1.81^{d}
	T3	6.00 ± 1.23^{e}	21.20 ± 1.92^{d}	10.40 ± 0.55^{e}	51.00 ± 3.08^{e}	12.2 ± 3.90^{cd}	64.4 ± 2.19^{f}	12.44 ± 0.62^{e}	64.65 ± 2.57^{f}
F value		39.64**	28.39**	69.53**	17.20**	4.14*	221.45**	98.02**	120.38**
SEM		0.39	1.07	0.30	2.37	0.96	0.50	0.24	0.25
CD (5%)		1.14	3.14	0.89	6.99	2.09	1.48	0.72	0.74
CV (%)		9.92	8.06	5.03	8.51	13.19	1.53	3.42	0.74

Where T1 is 125% of inorganic fertilizers, T2 is 100% of inorganic fertilizers, and T3 is 100% of organic manures

Different alphabets (a, b, c, d, and e) indicate the significant difference between the treatments with ($P < 0.05$) * and ($P > 0.01$) **, LSD test.

SEM: Standard errors of mean; CD: Critical difference; and CV: Coefficient of variance

Tiller numbers and plant height, (19.38 and 87.5 cm, respectively), were higher in the direct-seeded rice (DSR) with 125% of the recommended dose of inorganic N fertilizers (RDIF) (T_1), compared to other treatments. The lowest number of tillers and height of the plant (12.44 and 64.65 cm) were observed in the transplanting method with 100% application of organic manures (T_3). Growth attributes, such as plant height and the number of tillers of rice, showed a significant reduction under the transplanting method as compared to DSR, which is contradictory to many of the earlier studies (Hou et al. 2019; Lee et al. 2021; Surendran et al. 2021), since in general, transplanting method of cultivation results in higher growth and yield parameters. The possible reason for higher growth attributes in DSR might be due to the line sowing technique, maintaining the plant population, as well as timely weed management operation carried out, whereas in most of the earlier studies, line sowing was not adopted under DSR method of planting.

Similar to crop biometrics, yield parameters also showed that the nutrient management and method of planting significantly influenced the parameters, and the data are presented in Table 2. The results showed that 125% of the recommended dose of inorganic N fertilizers (RDIF) produced higher yield attributes, and it is statistically significant over the other treatments. Organic manure applied treatment resulted in the poor performance of crop growth parameters (Table 2 and Fig. 3). Similarly, among the method of planting, DSR performed better than transplanting in contrast with many of the earlier studies, which showed that transplanting results in higher yield attributes because of low plant population, higher growth of weeds in DSR methods

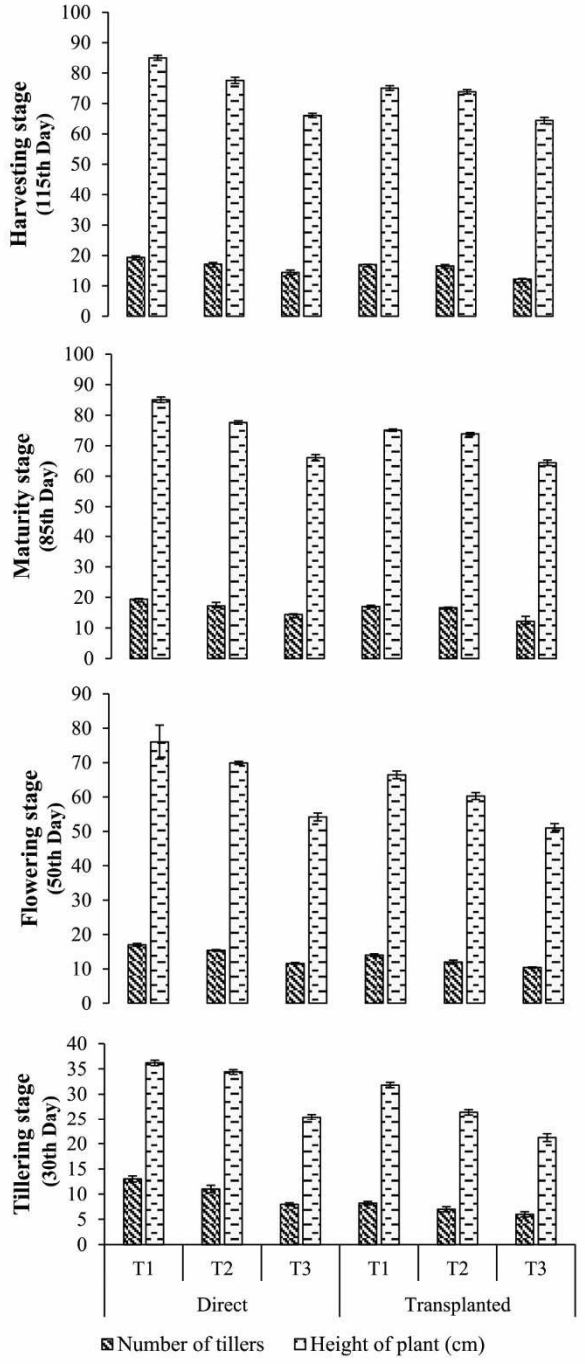

Fig. 3 Growth characteristics such as number of tillers and height of the rice plant *cv. Uma* are represented by its mean value of six replications. Error bar represented as the standard error (SE) of the six replications. Where T1 is 125% of inorganic fertilizers, T2 is 100% of inorganic fertilizers, and T3 is 100% of organic manures

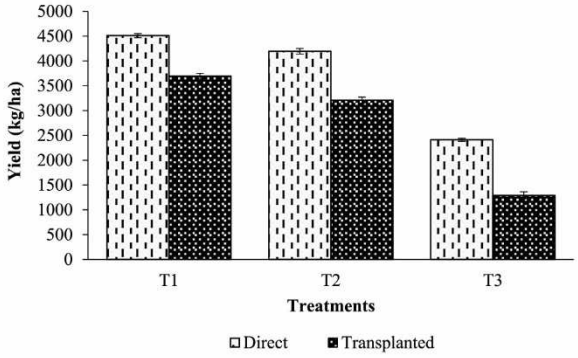

Fig. 4 Yield of rice *cv. Uma* is expressed in kilogram per hector and is represented as the mean value of six replications. Error bar represented as the standard error (SE) of the six replications. Where T1 is 125% of inorganic fertilizers, T2 is 100% of inorganic fertilizers, and T3 is 100% of organic manures

(Ali et al. 2014; Surendran et al. 2021). However, few studies reported DSR performed better than transplanting methods. Hassan and Behzad (2011) studies showed a similar result to the present study, in which the DSR method of planting had the best outcome on the total number of tillers, number of panicles, and yield. This might be due to the transplanting shock experienced by the transplanted rice seedlings during an early tillering stage, and it is very sensitive, resulting in lowering the growth and yield parameters whereas DSR gets reasonable adaptation time and performed better. Apart from this, in DSR, the adoption of line sowing technique, maintaining the plant population, as well as timely weed management operation might result in higher yield attributes.

Yield

The results showed that the method of planting and nutrient management practices significantly influenced the paddy yield. The results showed that DSR performed better than the transplanted method and concerning nutrient management, 125% of the recommended dose of inorganic N fertilizers resulted in higher yield compared to the organic manure application (Fig. 4). Higher quantity of nutrients (125%) significantly influenced the plant growth and other yield parameters, mainly because of increase in the availability of nutrients and favorable soil characteristics, which might have influenced the nutrient availability and ultimately resulted in higher growth and yield parameters. This is confirmed by the dry matter translocation from stems and leaves into grains increased significantly with increasing N application (Zhang et al. 2009).

Aerobic rice systems require more nitrogen than conventional rice to sustain yield but at the cost of higher N loss. Therefore, comprehensive understanding about the

N dynamics and N cycling of aerobic rice systems under irrigated conditions is necessary to intensify a sustainable rice yield while reducing N loss and environmental hazards. This raises an important question and that made us to probe the same in detail, and we found that even though N loss is major issue in both conventional and aerobic rice systems, although in the latter losses are relatively very high and only few studies have reported, which indicate that the N dynamics needs to be critically looked into before going for larger area of aerobic rice cultivation (Farooq et al. 2022).

The least yield was obtained with organic manure application treatment. The possible reason is that under organic manure application, the readily available nutrients for uptake might be less. However, review of the literature suggests that during the initial phase, the yield may be less in organic farming compared to the intensive chemical fertilizer application, but the long-term practice of organic farming will result in improvement of soil quality and ultimately resulting in higher productivity; hence, farmers need to be offset during this period with additional subsidies for the promotion of organic farming approaches.

The low yield obtained under the transplanting method is that plants might have suffered a setback when transplanted from the nursery, whereas, under DSR, plants might have adapted to the condition from the beginning (Ali et al. 2014). During the vegetative growth stage**,** adequate land submergence is necessary from transplanting to prevent damage to establishing seedlings and for proper root development, which might not have happened under aerobic rice cultivation. Earlier studies reported even under anaerobic rice, moisture stress occurring during the active tillering phase will reduce the yield by about 30% (Bouman et al. 2007). In India's Farmers Participatory Action Research Program (FPARP), DSR resulted in a higher production than a flooded field and a 20% water savings, but the reported yield gain was not observed in experimental plots (Gupta et al. 2003). But in another study, DSR produced higher yields (13–18%) and reduced the total water inputs (8–12%) in comparison with transplanted rice (Ishfaq et al. 2020). Adoption of line sowing technique, maintaining the plant population by proper gap filling as well as timely weed management operation, and availability of nutrients might result in higher yield. Even though yield increases have been observed, caution should be exercised before implementing this technique on a broad scale, since appropriate aerobic rice cultivars, optimum management practises, and other factors such as organic farming must be investigated.

Water saving

The total crop water requirement and net irrigation requirement were calculated based on the CROPWAT model for all three rice-growing seasons of Kerala for aerobic and anaerobic rice method of cultivation. The total water requirement for *Virippu* (Kharif), *Mundakan* (Rabi), and *Puncha* (summer) seasons for anaerobic (flooded) cultivation was 1589.9 mm, 1607.2 mm, and 1705.6 mm, whereas for aerobic cultivation, the total water requirement was 969.9 mm, 987.2 mm, and 1085.6 mm, respectively. The net irrigation requirement (NIR) for the aerobic rice is 286.6 mm, 650.4 mm, and 962.0 mm for *Virippu*, *Mundakan*, and *Puncha* seasons, respectively, whereas for anaerobic rice, NIR is 802.3 mm, 1607.2 mm, and 1582.0 mm for *Virippu*, *Mundakan*, and *Puncha* seasons, respectively. For projecting the savings in water requirement, *Puncha* (summer) season has been considered, mainly because summer season crops are mainly irrigated crops in Kerala and that might result in higher savings of water requirement, whereas the other two seasons are mostly rain-fed method of cultivation. The quantity of water savings for aerobic and flooded rice is shown in Table 3 and which showed water saving to the tune of 36.4% in the case of aerobic rice compared to flooded rice, and this is in accordance with many of the earlier studies (Ladha et al. 2003).

Figure 5 graphically represents the irrigational water savings, when 20, 40, 60, 80, and 100% of total rice cultivated areas of Kozhikode and Wayanad districts under flood cultivation are converted to the aerobic method of cultivation. These simulations resulted in water saving of 54.72–547.21 mm for 10–100% of the total rice cultivated areas of Kozhikode and Wayanad districts. In other words, when an anaerobic method is converted to an aerobic method of rice cultivation results in 7.15–35.77% of water saving. This is similar to some of the earlier reports, which have reported water savings of 35–57% for DSR sown in non-puddled soil with the soil kept near field capacity (FC) saturation compared with continuously flooded (5 cm) transplanted rice (Ladha et al. 2003; Reddy et al. 2020; Chadhar et al. 2020). The adoption of water-saving techniques in rice not only increases the paddy yield but also increases carbon sequestration, helps in resource saving, and reduces the emission of greenhouse gases (GHGs) (Yang et al. 2017).

Conclusion

The increasing shortage of water resources has led to the development and adoption of an aerobic rice system, which saves water input and increases water productivity by reducing water use during land preparation and limiting seepage, percolation, and evaporation during the period of cultivation. In this study, the method of planting and nutrient management was compared under aerobic rice cultivation. The results showed that DSR performed better than the transplanted method under aerobic rice, and with respect to nutrient management, 125% of the recommended dose

Table 3 Irrigation requirement output for *Puncha* rice seasons using CROPWAT model for the experiment in comparison with the anaerobic rice

Stage	Anaerobic rice			Aerobic rice		
	ETc	ER	IR	ETc	ER	IR
	mm/dec	mm/dec	mm/dec	mm/dec	mm/dec	mm/dec
Nurs	3.9	6.0	0.0	3.9	6.0	0.0
Nurs/LPr	39.5	4.3	35.2	39.5	4.3	35.2
Init	96.9	2.3	94.6	56.9	2.3	54.6
Init	98.9	0.0	98.9	58.9	0.0	58.9
Deve	104.8	0.2	104.6	64.8	0.2	64.6
Deve	102.6	0.3	102.3	62.6	0.3	62.3
Deve	104.6	0.1	104.5	64.6	0.1	64.5
Deve	97.0	1.8	95.2	57.0	1.8	55.2
Mid	107.8	2.6	105.2	67.8	2.6	65.2
Mid	109.3	3.6	105.7	69.3	3.6	65.7
Mid	115.1	9.2	105.9	75.1	9.2	65.9
Late	110.8	14.1	96.7	70.8	14.1	56.7
Late	110.0	18.7	91.3	70.0	18.7	51.3
Late	106.1	28.0	78.1	66.1	28.0	38.1
Late	98.3	34.5	63.8	58.3	34.5	23.8
Total	1405.6		1282.0	885.6		762.0
Land preparation	300.0		300.0	200.0		200.0
Total water requirement	1705.6		1582.0	1085.6		962.0

Where ET_C Crop evapotranspiration, *ER* Effective rainfall, *IR* Irrigation requirement, *Nurs* Nursery phase of rice cycle, *LPr* Land preparation phase, *Init* Initial phase, *Deve* Developmental phase, *Mod* Middle phase, and *Late* Late phase

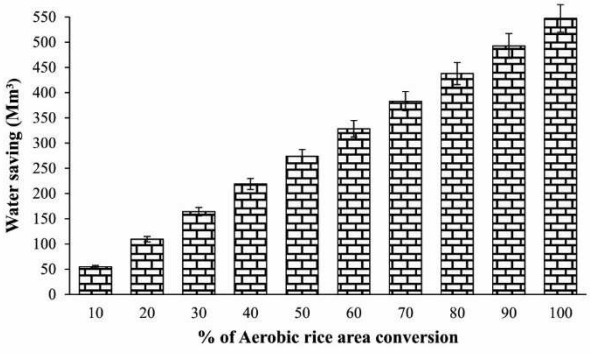

Fig. 5 Irrigational water savings from converting different percentage of areas of flood cultivation to aerobic cultivation

of inorganic N fertilizers (RDIF) produced a higher yield compared to the organic manure application.

In addition, water saving was to the tune of 36.4% when compared with the FAO-CROPWAT-based anaerobic rice water requirement. To conclude, the direct method of line sowing along with 125% of the recommended dose of inorganic fertilizers will result in higher crop and water productivity. Hence, it is suggested that the agriculture department and policymakers can promote the aerobic method of rice cultivation with direct line sowing, which will result in huge quantities of saving of water and yield improvement. The adoption of water-saving techniques in rice not only increases the paddy yield but also increases carbon sequestration, helps in resource saving, and reduces the emission of greenhouse gases (GHGs), since Kerala is moving toward carbon neutral state by 2050.

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Author contributions **US** conceptualized the work, and **PS** conducted the experiment and did the soil analysis and written the first draft. Both the authors reviewed the manuscript, and final version has been made.

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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare that they have no competing or conflicting interests.

Consent for publication Not applicable.

Ethics approval and consent to participate Not applicable.

References

Ali A, Erenstein O, Rahut DB (2014) Impact of direct rice-sowing technology on rice producers earnings: empirical evidence from Pakistan. Develop Stud Res Open Access J 1(1):244–254

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration - guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper, FAO, Rome

Arbat G, Cufí S, Duran-Ros M, Pinsach J, Puig-Bargués J, Pujol J, Ramírez de Cartagena F (2020) Modeling approaches for determining dripline depth and irrigation frequency of subsurface drip irrigated rice on different soil textures. Water 12(6):1724

Barnaby JY, McClungAM EJD, Pinson SR (2022) Identification of quantitative trait loci for tillering, root, and shoot biomass at the maximum tillering stage in rice. Sci Rep 12(1):1–13

Bhatt R, Kukal SS, Busari MA, Arora S, Yadav M (2016) Sustainability issues on rice–wheat cropping system. Int Soil Water Conserv Res 4(1):64–74

Bhatt R, Hossain A, Hasanuzzaman M (2019) Adaptation strategies to mitigate the evapotranspiration for sustainable crop production: a perspective of rice-wheat cropping system. Agronomic crops. Springer, Singapore, pp 559–581

Bouman BA, Humphreys E, Tuong TP, Barker R (2007) Rice and Water. Adv Agron 92:187–237

Chadhar AR, Nadeem MA, Ali HH, Safdar ME, Raza A, Adnan M, Hussain M, Ali L, Javaid MM (2020) Quantifying the impact of plant spacing and critical weed competition period on fine rice production under the system of rice intensification. Int J Agri Biol 24(5):1142–1148

Chakraborty D, Ladha JK, Rana DS, Jat ML, Gathala MK, Yadav S, Rao AN, Ramesha MS, Raman A (2017) A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. Sci Rep 7(1):1–11

Day PR (1965) Particle fractionation and particle-size analysis. Methods of soil analysis: part 1 physical and mineralogical properties. Includ Stat of Measure Sampl. Wiley, New York, pp 545–567

de Avila LA, Martini LFD, Mezzomo RF, Refatti JP, Campos R, Cezimbra DM, Machado SLO, Massey JH, Carlesso R, Marchesan E (2015) Rice water use efficiency and yield under continuous and intermittent irrigation. Agron J 107(2):442–448

de Borja Reis AF, Vasconcelos ALS, de Almeida REM, Lago BC, Dias CTS, Favarin JL (2018) Relationship of nitrogen and crop performance in aerobic rice and continuous flooding irrigation in weathered tropical lowland. Eur J Agron 95:14–23

Dhillon SK, Bhatia D, Gill GK, Singh P, Mangat GS (2022) Biotic and Abiotic Stress Tolerance in Plants under Changing Climatic Conditions. Punjab Agricultural University Website.http://web.pau.edu/caftpbg/. Accessed September 6, 2022

DOES (2022) Agricultural statistics at a glance. Department of Economics and Statistics, Government of Kerala, India

Doorenbos J, Kassam A (1979) Yield response to water. FAO Irrigation and Drainage Paper, FAO, Rome

Dwivedi BS, Shukla AK, Singh VK, Yadav RL (2003) Improving nitrogen and phosphorus use efficiencies through inclusion of forage cowpea in the rice–wheat systems in the Indo-Gangetic Plains of India. Field Crops Res 80(3):167–193

Farooq MS, Uzair M, Maqbool Z, Fiaz S, Yousuf M, Yang SH, Khan MR (2022) Improving Nitrogen Use Efficiency in Aerobic Rice Based on Insights Into the Ecophysiology of Archaeal and Bacterial Ammonia Oxidizers. Front Plant Sci 13:913204. https://doi.org/10.3389/fpls.2022.913204

Gabr MES (2022) Management of irrigation requirements using FAO-CROPWAT 8.0 model: a case study of Egypt. Model Earth Syst Environ 8(3):3127–3142

Gabr ME, Fattouh EM (2021) Assessment of irrigation management practices using FAO-CROPWAT 8, case studies: Tina Plain and East South El-Kantara, Sinai. Egypt Ain Shams Eng J 12(2):1623–1636

Gopinath PP, Parsad R, Joseph B, Adarsh VS (2021) GrapesAgri1: collection of shiny apps for data analysis in agriculture. J Open Source Softw 6(63):3437

Gupta RK, Naresh RK, Hobbs PR, Jiaguo Z, Ladha JK (2003) Sustainability of post-Green Revolution agriculture: the rice–wheat cropping systems of the Indo-Gangetic Plains and China. Improving the productivity and sustainability of rice-wheat systems: issues and Impacts. Wiley, New York, pp 1–25

Hafeez-ur-Rehman AN, Awan MI, Muhammad I, Mubshar H, Shakeel A, Muhammad F (2019) Direct seeding in rice: problems and prospects. Agronomic Crops: 1: production Technologies. Springer, Singapore, pp 199–222

Hanway JJ, Heidel H (1952) Soil analysis methods as used in Iowa state college soil testing laboratory, bulletin 57. Iowa State College of Agriculture, Iowa, USA, p 131

Hassan A, Behzad K (2011) Assessment of direct seeded and transplanting methods of rice cultivars in the northern part of Iran. Afr J Agric Res 6(31):6492–6498

Hou W, Khan MR, Zhang J, Lu J, Ren T, Cong R, Li X (2019) Nitrogen rate and plant density interaction enhances radiation interception, yield and nitrogen use efficiency of mechanically transplanted rice. Agric Ecosyst Environ 269:183–192

Ishfaq M, Akbar N, Anjum SA, Anwar-Ijl-Haq M (2020) Growth, yield and water productivity of dry direct seeded rice and transplanted aromatic rice under different irrigation management regimes. J Integr Agric 19(11):2656–2673

Jackson M (1967) Soil chemical analysis prentice. Hall of India Private Limited, New Delhi

Kerala Agricultural University (KAU) (2016) Package of Practices RecommendationsKerala Agricultural University. Thrissur, Kerala

Ladha JK, Dawe D, Pathak H, Padre AT, Yadav RL, Singh B, Singh Y, Singh Y, Singh P, Kundu AL, Sakal R, Ram N, Regmi AP, Gami SK, Bhandari AL, Amin R, Yadav CR, Bhattarai EM, Das S, Aggarwal HP, Gupta RK, Hobbs PR (2003) How extensive are yield declines in long-term rice–wheat experiments in Asia? Field Crops Res 81(2–3):159–180

Lee H, Hwang W, Jeong J, Yang S, Jeong N, Lee C, Choi M (2021) Physiological causes of transplantation shock on rice growth inhibition and delayed heading. Sci Repo 11(1):1–13

Mondal R, Goswami S, Goswami SB, Jana K (2020) Effect of different nutrient management practices on growth, grain yield, production economics, soil nutrient availability of transplanted kharif rice (*Oryza sativa* L.) and correlation studies. J Crop Weed 16(1):172–179

Olsen SR (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. US Department of Agriculture, US

Prasad R (2011) Aerobic rice systems. Advances in agronomy. Academic Press Inc, US, pp 207–247

Reddy AK, Prudhvi N, Mehta CM (2020) Direct seeded rice-future of rice (*Oryza sativa*) cultivation. Int J Res Anal Rev 7(4):279–291

Saber M, Mokhtar M, AbudeifBakheit AM, Elfeky MG, Mostafa A, Sefelnasr A, Kantoush SA, Sumi T, Hori T, Hamada A (2022) An integrated assessment approach for fossil groundwater quality and crop water requirements in the El-Kharga Oasis Western Desert Egypt. J Hydrol: Region Stud 40:101016. https://doi.org/10.1016/j.ejrh.2022.101016

Shah M, Vijayshankar PS, Harris F (2021) Water and agricultural transformation in India: a symbiotic relationship-I. Econ Polit Wkly 56(29):43–55

Shekhawat K, Rathore SS, Chauhan BS (2020) Weed management in dry direct-seeded rice: a review on challenges and opportunities for sustainable rice production. Agronomy 10(9):1264

Subbiah BV, Asija GL (1956) A raped processor of determination of available nitrogen in nitrogen in soil. Curr Sci 25:259–260

Surendran U, Sushanth CM, Mammen G, Joseph EJ (2015) Modelling the crop water requirement using FAO-CROPWAT and assessment of water resources for sustainable water resource management: a case study in Palakkad district of humid tropical Kerala, India. Aquat Procedia 4:1211–1219

Surendran U, Sushanth CM, Mammen G, Joseph EJ (2017) FAO-CROPWAT model-based estimation of crop water need and appraisal of water resources for sustainable water resource management: pilot study for Kollam district–humid tropical region of Kerala, India. Curr Sci 112:76–86

Surendran U, Raja P, Jayakumar M, Subramoniam SR (2021) Use of efficient water saving techniques for production of rice in India under climate change scenario: a critical review. J Clean 309:127272

Wakley A, Black IA (1965) an examination of the method for determining soil organic matter and proposed modification of the acid titration method. J Soil Sci 37:29–38

Yang J, Zhou Q, Zhang J (2017) Moderate wetting and drying increases rice yield and reduces water use, grain arsenic level, and methane emission. Crop J 5(2):151–158

Yoshida S (1981) Fundamentals of rice crop science, international rice research institute. Los Baños, Laguna

Zhang L, Lin S, Bouman BAM, Xue C, Wei F, Tao H, Yang X, Wang H, Zhao D, Dittert K (2009) Response of aerobic rice growth and grain yield to N fertilizer at two contrasting sites near Beijing. China Field Crops Res 114(1):45–53

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(Affiliated to TAMIL NADU AGRICULTURAL UNIVERSITY)

and

ALL INDIA AGRICULTURAL STUDENTS ASSOCIATION

Certificate of Participation

This is to certify that Dr./ Mr./ Mrs./ Ms. P. SRUTHI Ph.D. Scholar

CWRDM. Kerala has participated and presented a paper (Oral/Poster) at the **'International Conference on Climate Resilient Agriculture for Sustainable Agricultural Productivity (ICRSP-2023)'** under the theme **'Crop Management'** jointly organized by Mother Terasa College of Agriculture and All India Agricultural Students Association during March 31, 2023.

Organizing Secretary (ICRSP 2023)	State President TN - (AIASA)	Principal (MTCA)	Chairman (MTCA)

KSCSTE-CENTRE FOR WATER RESOURCES DEVELOPMENT AND MANAGEMENT

KSCSTE

KSCSTE-CWRDM

CERTIFICATE

This is to certify that Ms. Sruthi P

has presented a paper on Assessing the influence of different organic management practices on growth and yield of paddy.

at the International Conference on "Water and Environmental Management, WEM-2022" organized by KSCSTE - Centre for Water Resources Development and Management (CWRDM) during 22-24, June, 2022 at CWRDM Head Quarters, Kozhikode, Kerala.

Organizing Secretary
DR. RESMI T R
SENIOR SCIENTIST, CWRDM

Chairperson
DR. MANOJ P SAMUEL
EXECUTIVE DIRECTOR, CWRDM

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III Indian National Ground Water Conference

on GROUNDWATER RESOURCES MANAGEMENT FOR SUSTAINABLE DEVELOPMENT: SPECIAL EMPHASIS ON COASTAL AND URBAN ENVIRONMENT

INGWC-2020

18th to 20th February 2020

CERTIFICATE

This is to certify that Dr./Mr./Ms. Sruthi. P

has attended /presented paper entitled 'Assessing the influence of nutrient management & Method of Irrigation on two different Rice Cultivars'

in the Indian National Conference on *Groundwater Resources Management for Sustainable Development: Special Emphasis on Coastal and Urban Environment* organised by Centre for Water Resources Development and Management (CWRDM), Kozhikode, India on 18th to 20th February 2020.

Er. C M Sushanth
Convener

CALICUT

Dr. A B Anitha
Executive Director

Ms. Sruthi P
India

November 28, 2019

CLIFF–GRADS

Climate, Food and Farming Network GRA Development Scholarships

Thank you for your application for a Climate, Food and Farming Network and Global Research Alliance Development Scholarships (CLIFF-GRADS) award.

It is our pleasure to inform you that your application has been selected for a grant of **$12,000 USD** for a **6 month** research stay as specified by the project outline at the **IRTA - Marine and Continental Waters Program, Spain,** to collaborate on the project *"Post-harvest management in rice paddy fields for carbon budget optimization"*. Congratulations!

Dr. Maite Martínez-Eixarch (*maite.martinezeixarch@irta.cat)* will be your host supervisor and contact person before and during the research stay. We kindly request that you contact your host supervisor as soon as possible in order to prepare the research visit and project.

The CLIFF-GRADS Programme collaborates with Aarhus University, Denmark. Aarhus University administers the grant and will transfer the amount to your bank account before the end of January 2020. An initial disbursement of **$11,000 USD** will be disbursed upon signing of this contract. A final disbursement of **$1,000 USD** will be transferred once the research visit is underway and CLIFF-GRADS has received confirmation of satisfactory progress from the research supervisor.

Please complete the enclosed bank details form for administration of your grant and return it to Jytte Christensen (e-mail: Jytte.Christensen@agro.au.dk) before **December 6, 2019** together with a signed version of this grant letter.

The grant must be used to support living and research costs at the host institution including visas, travel, housing, meals, research materials and services etc. Grant funds are not to be used for tuition, fees, or unrelated personal costs.

Please note that the scientific visit must be completed by **December 31, 2020**.

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Attached to this letter is also a list of **Reporting Requirements**, the **CLIFF-GRADS policy on Sharing Information Products** and **Guidelines for hosts and students**. We recommend you to get familiar with the text in these documents.

Please note that publications, presentations, etc. resulting from this research must acknowledge The Global Research Alliance on Agricultural Greenhouse Gases (GRA), CGIAR's Climate Change Agriculture and Food Security programme (CCAFS) as well as your host institution and any additional donors. Suggested text is attached as an appendix to this letter.

Your acceptance of the CLIFF-GRADS Award is acknowledgement of your agreement to the terms in this letter and attachments.

A signed version of this letter must be returned to Jytte.Christensen@agro.au.dk, together with your bank details before **December 6, 2019.** This will serve as confirmation of your acceptance of the fellowship.

We again thank you for your interest and congratulate you on this award.

Ciniro Costa Junior
Science Officer,
CCAFS

Hayden Montgomery
Special Representative, GRA

Jytte Christensen
Department Secretary,
Department of Agroecology
Aarhus University

Date:

Signature of recipient:

Sruthi P

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