

**UNDERSTANDING THE INTERACTIONS BETWEEN
SHOREBIRDS AND THEIR PREY WITH EMPHASIS ON THEIR
FORAGING BEHAVIOUR IN SELECTED STOP OVER SITES**

PhD Thesis Submitted to the University of Calicut for the
Award of the Degree of
DOCTOR OF PHILOSOPHY IN ZOOLOGY
(Under the Faculty of Science)

Submitted by

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Under the Guidance and Supervision of

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3.	Name of the Supervisor	Dr. JOBIRAJ T	
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DECLARATION

I hereby declare that the work presented in the thesis entitled **“UNDERSTANDING THE INTERACTIONS BETWEEN SHOREBIRDS AND THEIR PREY WITH EMPHASIS ON THEIR FORAGING BEHAVIOUR IN SELECTED STOP OVER SITES”** is based on the original work done by me under the guidance of **Dr. JOBIRAJ T. (*guide*)**, Associate professor, Department of Zoology, Govt. College Kodanchery, **Dr. THEJASS P. (*Joint guide*)**, Associate Professor, Department of Zoology, Govt. College Madappally and **Dr. AARIF K. M. (*Joint guide*)**, Research scientist, Division of Terrestrial Ecology, Centre for Environment and Marine Studies, Research & Innovation, King Fahd University of Petroleum & Minerals, Kingdom of Saudi Arabia, 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



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Dedication

To my parents

For allowing me to embrace every opportunity

To my Guru, Dr. K. M. Aarif

*For his selfless sacrifices
and the light of wisdom he brought to my soul*

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ATHIRA T.R.

ABSTRACT

Shorebirds are critical indicators of coastal ecosystem health, yet their populations are declining globally due to habitat degradation, resource depletion, and environmental pollution. This thesis synthesizes a decade of research (2010–2023) on the population dynamics, foraging ecology, habitat use, contaminant exposure, and novel behavioural adaptations of migratory shorebirds along the west coast of India.

Long-term monitoring revealed significant population declines of near threatened Eurasian Curlew and Bar-tailed Godwit, and their shifts in habitat use from traditional mudflats to sand beaches and mangroves. Foraging observations and dietary analyses, including droppings assessments, demonstrated species-specific prey preferences, with Bar-tailed Godwits predominantly consuming polychaetes and medium-sized crabs in mangroves, while Eurasian Curlews exhibited a preference for *Cosmonotus* crabs and small fishes on sand beaches. Prey capture rates varied across habitats, with mangroves supporting higher foraging success, although a marked decline in capture efficiency over time underscored the impacts of habitat degradation. The pandemic-induced reduction in human disturbances temporarily improved foraging conditions, further highlighting anthropogenic pressures on shorebird populations.

Long-term changes in environmental variables led to significant decline in zooplankton abundance, indicating severe habitat degradation and reduced prey base for higher trophic levels. Distinct foraging behaviours were documented, including the continuous stitching movement of Bar-tailed Godwits in two distinct modes, straight-line and zigzag, optimizing prey capture while minimizing energy expenditure in resource-scarce environments. Additionally, foot trembling behaviour was observed across multiple shorebird species, including both visual and tactile foragers, indicating a functional response to habitat constraints. Adaptive prey transport mechanisms, facilitating small prey profitability were

identified, enhancing capture efficiency in degraded mudflats. Additionally, the study documented a concerning shift in shorebird recruitment patterns, with increased over-summering in agroecosystems coinciding with declining juvenile abundance in coastal habitats.

Comprehensive assessments of microplastic contamination revealed high levels of polyethylene, polypropylene, and polystyrene in water, sediment, macroinvertebrate prey, and shorebird droppings, establishing trophic transfer pathways. Heavy metal analyses detected elevated concentrations of zinc, copper, cobalt, chromium, lead, and cadmium in droppings, further raising concerns about pollutant bioaccumulation. The prevalence of microfibers and polymer-specific ingestion patterns among shorebirds emphasized the urgent need for targeted conservation measures.

By integrating ecological monitoring with contamination assessments, this thesis provides a comprehensive framework for understanding the complex interactions shaping shorebird populations. The findings underscore the need for immediate conservation interventions, including habitat restoration, pollution mitigation, and adaptive management strategies to safeguard migratory shorebirds in rapidly changing coastal ecosystems in India.

സംഗ്രഹം

തീരുപക്ഷികൾ, തീരദേശപരിസ്ഥിതിയുടെ ആരോഗ്യത്തിന്റെ നിർണായക സൂചകങ്ങളാണ്. എന്നാൽ ആവാസവ്യവസ്ഥയുടെ നാശം, വിഭവങ്ങളുടെ ദൗർലഭ്യം, മലിനീകരണം എന്നിവ മൂലം ഇവയുടെ ജനസംഖ്യ ആഗോളതലത്തിൽ കുറയുകയാണ്. ഇന്ത്യയുടെ പടിഞ്ഞാറൻ തീരങ്ങളിലെ ദേശാടകരായ തീരുപക്ഷികളുടെ ജനസംഖ്യാഗതികൾ, ഭക്ഷ്യശീലങ്ങൾ, ആവാസ ഉപയോഗം, മാലിന്യസമ്പർക്കം, നൂതനമായ പെരുമാറ്റാനുരൂപണങ്ങൾ എന്നിവയെക്കുറിച്ച് 2010 മുതൽ 2023 വരെയുള്ള ഒരു ദശാബ്ദത്തിലേറെ നീണ്ട ഗവേഷണഫലങ്ങൾ ഈ പ്രബന്ധത്തിൽ സംഗ്രഹിച്ചിരിക്കുന്നു.

ദീർഘകാല നിരീക്ഷണത്തിൽ, വംശനാശഭീഷണി നേരിടുന്ന വാൾകൊക്കൻ, വരവാലൻ ഗോഡ്വിറ്റ് എന്നീ പക്ഷികളുടെ ജനസംഖ്യയിൽ വലിയ കുറവ് ഉണ്ടായതും, പരമ്പരാഗത ചളിപ്പാടങ്ങളിൽ നിന്ന് കടൽത്തീരങ്ങൾ, കണ്ടൽക്കാടുകൾ ഉൾപ്പെടെയുള്ള ആവാസവ്യവസ്ഥകളിലേക്ക് ഇവയുടെ ആവാസ ഉപയോഗത്തിൽ മാറ്റം വന്നതും കണ്ടെത്തി. ഭക്ഷ്യശീലങ്ങൾ, വിസർജ്യ പരിശോധനകൾ എന്നിവയിൽ നിന്നുള്ള വിശകലനത്തിൽ, വരവാലൻ ഗോഡ്വിറ്റുകൾ കണ്ടൽക്കാടുകളിൽ പ്രധാനമായും ഞാഞ്ഞൂലുകളെയും ഇടത്തരം വലിപ്പമുള്ള ഞെണ്ടുകളെയും ഭക്ഷിക്കുന്നതും, വാൾകൊക്കൻമാർ തീരങ്ങളിൽ പ്രധാനമായും കോസ്മോണോട്ടസ് ഞെണ്ടുകളെയും ചെറുമീനുകളെയും ഭക്ഷിക്കുന്നതും കണ്ടെത്തി. ആവാസവ്യവസ്ഥ അനുസരിച്ച് ഈ പിടിക്കലിന്റെ വിജയനിരക്ക് വ്യത്യാസപ്പെട്ടിരിക്കുന്നു. കണ്ടൽക്കാടുകളിൽ കൂടുതൽ വിജയകരമായിരുന്നു വെങ്കിലും, കാലക്രമേണ ഈ വിജയനിരക്ക് കുറഞ്ഞത് ആവാസനാശത്തിന്റെ ദോഷഫലങ്ങൾ വ്യക്തമാക്കുന്നു. കോവിഡ്-19 മഹാമാരിക്കാലത്ത് മനുഷ്യരുടെ ഇടപെടലുകൾ കുറയുന്നത് താൽക്കാലികമായി ഭക്ഷ്യശീലങ്ങൾക്ക് അനുകൂലമായ സാഹചര്യങ്ങൾ സൃഷ്ടിച്ചു, മനുഷ്യപ്രഭാവം തീരുപക്ഷികളെ എത്രത്തോളം ബാധിക്കുന്നു എന്നതും ഇതിലൂടെ വ്യക്തമാകുന്നു.

പരിസ്ഥിതിയിലുണ്ടായ ദീർഘകാല വ്യതിയാനങ്ങൾ ജന്തുപ്ലവകങ്ങളുടെ സാന്ദ്രതയിൽ ഗണ്യമായ കുറവ് വരുത്തിയത്, ആവാസവ്യവസ്ഥയുടെ ഗുരുതരമായ നശീകരണവും ഉയർന്ന ടോഫിക് തലങ്ങളിൽ ഉള്ള ജീവികൾക്ക് ഇരലഭ്യത കുറയുന്നതിനെയും സൂചിപ്പിക്കുന്നു. വിഭവക്ഷാമം അനുഭവപ്പെടുന്ന ആവാസ- വ്യവസ്ഥകളിൽ, ഊർജ്ജനഷ്ടം കുറച്ച് മതിയായ തോതിൽ ഇരപിടിക്കാൻ വരവാലൻ ഗോഡ്വിറ്റുകൾ, നേർരേഖയിലും സിഗ്സാഗ് രീതിയിലും ഉള്ള തുടർച്ചയായ സ്ലിച്ചിംഗ് ചലനങ്ങൾ പ്രദർശിപ്പിക്കുന്നതായി രേഖപ്പെടുത്തി. അതോടൊപ്പം, കാഴ്ചയും സ്പർശവും ഉപയോഗിച്ച് ഇരതേടുന്ന വിവിധയിനം തീരുപക്ഷികൾ ഫൂട് ട്രാക്കിംഗ് എന്ന ഇരതേടൽ സ്വഭാവം കാണിക്കുന്നതും കണ്ടെത്തി. ഇത് ആവാസവ്യവസ്ഥയിലെ പരിമിതികളോടുള്ള പ്രതികരണമായി വിലയിരുത്തുന്നു.

നശീകരണത്തിനു വിധേയമായ ചളിപ്പാടങ്ങളിൽ ചെറിയ ഇരകളെ കൂടുതലായി പിടിക്കാൻ വേണ്ടി അനുയോജ്യമായ പുതിയ ഇരവാഹക രീതികൾ ഉപയോഗിക്കുന്നതായും കണ്ടെത്തി. കൂടാതെ, തീരദേശ ആവാസവ്യവസ്ഥകളിൽ തീരപ്പക്ഷിക്കുഞ്ഞുങ്ങളുടെ എണ്ണം കുറയുന്നതോടൊപ്പം, കാർഷിക ആവാസ- വ്യവസ്ഥകളിൽ വന്ന ജനസംഖ്യാവർദ്ധനവുമടക്കം, റിക്രൂട്ട്മെന്റ് രീതികളിൽ വന്ന ആശങ്കാജനകമായ മാറ്റവും ഈ പഠനം രേഖപ്പെടുത്തുന്നു.

മൈക്രോപ്ലാസ്റ്റിക് മലിനീകരണത്തെക്കുറിച്ചുള്ള സമഗ്രമായ വിലയിരുത്തലുകൾ ജലത്തിലും, മണ്ണിലും, അകശേരുകികളായ ഇരകളിലും, തീരപ്പക്ഷികളുടെ വിസർജ്യത്തിലും പോളിഎത്തിലീൻ, പോളിപ്രൊപ്പിലീൻ, പോളിസ്റ്ററിൻ എന്നിവയുടെ ഉയർന്ന അളവ് കണ്ടെത്തി. ഇതിലൂടെ ഭക്ഷ്യശൃംഖല വഴി ഇവയുടെ കൈമാറ്റം നടക്കുന്നതായും തെളിയിക്കപ്പെട്ടു. തീരപ്പക്ഷികളുടെ വിസർജ്യത്തിൽ നടത്തിയ ഘനലോഹങ്ങളുടെ വിശകലനത്തിൽ സിങ്ക്, കോപ്പർ, കോബാൾട്ട്, ക്രോമിയം, ലെഡ്, കാഡ്മിയം എന്നിവയുടെ അളവ് കൂടുതലാണെന്ന് കണ്ടെത്തിയിട്ടുണ്ട്. ഇത് മലിനീകരണ പദാർത്ഥങ്ങളുടെ ജൈവസാന്നിധ്യത്തെക്കുറിച്ചുള്ള ആശങ്ക വർദ്ധിപ്പിക്കുന്നു. തീരപ്പക്ഷികൾ മൈക്രോഫൈബറുകളും പ്രത്യേക പോളിമറുകളും കൂടുതലായി ഭക്ഷിക്കുന്നതായി കാണപ്പെട്ടതിനാൽ തന്നെ ശ്രദ്ധാപൂർവ്വമായ സംരക്ഷണ നടപടികൾ അത്യാവശ്യമാണ്.

പരിസ്ഥിതി നിരീക്ഷണവും മലിനീകരണ വിലയിരുത്തലും സംയോജിപ്പിച്ചുകൊണ്ട്, ഈ പ്രബന്ധം തീരപ്പക്ഷി ജനസംഖ്യയെ രൂപപ്പെടുത്തുന്ന സങ്കീർണ്ണ ഇടപെടലുകൾ മനസ്സിലാക്കുന്നതിനുള്ള സമഗ്രമായ മാതൃക നൽകുന്നു. ആവാസപുനരുദ്ധാരണവും മലിനീകരണ നിയന്ത്രണവും, അനുയോജ്യമായ മാനേജ്മെന്റ് തന്ത്രങ്ങളും അടങ്ങുന്ന അടിയന്തിര സംരക്ഷണ നടപടികൾ ഇന്ത്യയിലെ വേഗത്തിൽ മാറുന്ന തീരദേശ പരിസ്ഥിതിയിലെ ദേശാടകരായ തീരപ്പക്ഷികളെ സംരക്ഷിക്കാൻ അനിവാര്യമാണ്.

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GENERAL INTRODUCTION

Migratory shorebirds (Charadriidae) serve as crucial global indicators for assessing the health of delicate coastal ecosystems (Mathot et al., 2018; Sutherland et al., 2012). Shorebirds undertake some of the longest migrations known and are experiencing significant population declines globally (Aarif et al., 2014, 2017; Shamna et al., 2023; van de Pol et al., 2024). Poor habitat quality, affected by anthropogenic activities and global climate change, is the broad cause of their decline. Their low reproductive rates and the severe degradation of critical wintering habitats hinder their ability to recover from population declines.

Migration is considered to have evolved as an adaptation to exploit seasonal peaks in resource abundance while avoiding seasonal resource depletion during the non-breeding periods. In order to successfully finish their long-distance migration flights, constrained within a narrow window of time, shorebirds must accumulate large fuel reserves in the form of fat and protein. Hence, the critical wintering and stop-over sites of shorebirds are characterized by increased primary productivity and higher abundance of macrobenthic prey items, which are favorably influenced by suitable environmental variables, organic matter, and nutrients from terrestrial and marine sources. Thus, for successful migration, they require high-quality wintering and stop-over sites that allow efficient and opportunistic foraging strategies for refueling which, thus, ensure the survival and timely departure of the migratory shorebirds from wintering sites. This will directly affect their winter survival, subsequent migration, and breeding success (Jackson et al., 2024).

Long-distance migration imposes significant energy costs, necessitating efficient foraging strategies to meet their high-energy demands (Kersten & Piersma, 2002). Consequently, the spatiotemporal distribution of shorebirds in intertidal areas depends on prey diversity, density, and availability to maximize energy intake (Jourdan et al., 2021). Given that shorebirds migrate great distances and inhabit various kinds of habitats throughout their annual cycle, dietary flexibility is advantageous for exploiting variable resources (Isacch et al., 2005). Food preferences and foraging strategies adopted by different species vary considerably,

which has important implications on the effect of habitat degradation. Their local distribution is influenced by food availability and feeding adaptations (Fonseca et al., 2017).

Changes in intertidal foraging grounds can impact energy budgets and patterns of abundance and distribution of shorebirds (Calle et al., 2016), potentially affecting species survival. Organisms facing challenges in maintaining a positive energy budget may exhibit coping mechanisms such as spatial adjustments (Piersma, 2012), behavioural modifications (Sydeman et al., 2001), or phenotypic adaptations (Piersma & van Gils, 2011). Specialist species, which have a narrow trophic niche, face particular challenges when food availability varies spatially and temporally, impacting individual survival and population persistence.

Specialization reduces interspecific competition by decreasing niche overlap between species (Chesson, 2000). However, spatiotemporal variations in food availability can influence dietary patterns and species distribution (Hughes, 2000). In this context, intraspecific dietary adjustment, or trophic plasticity, can be advantageous for home range expansion, persistence in human-impacted areas, and population differentiation through local adaptation (Mendes et al., 2009; Michel et al., 2016). Shorebirds exhibit a variety of beak morphologies associated with their foraging strategies and dietary preferences (Gliesch et al., 2023). Understanding diet is key to comprehending species interactions and the structure of the food web. Enhancing knowledge of the diets of endangered or threatened wildlife is crucial for developing effective conservation strategies tailored to specific species (Hacker et al., 2021).

Migratory shorebirds travel back and forth along migratory flyways. Flyways are broadly defined areas over which birds migrate on a regular basis between breeding and non-breeding areas, including all areas used in between as staging areas and stopover sites. The Central Asian Flyway (CAF) is the smallest flyway (Aarif et al., 2014), in terms of area of coverage, and least studied among the

world's flyways. The CAF encompasses primarily the Indian subcontinent in the south and extends to the central portion of Russia and its surrounding areas. Indian coasts endowed with different ecosystems along its 8100 km long stretch (Raghunathan et al., 2019), are among the major wintering grounds for migratory shorebirds in CAF (Aarif et al., 2020). During this season, migratory shorebirds are prominently found along India's west coast, particularly within the Kadalundi Vallikkunnu Community Reserve (KVCR), which features intertidal mudflats, mangroves, and sand beaches (Rashiba et al., 2022). The importance of intertidal mud ecosystems as crucial habitats for shorebirds, providing diverse feeding opportunities, is well-documented (Mathot et al., 2018). Mudflats of KVCR, exposed during low tide, support a rich diversity and abundance of polychaete worms, followed by crustaceans, whereas mangroves exhibit higher crustacean diversity and abundance (Aarif, 2009; Aarif et al., 2014, 2021a). Adjacent sandy beaches, featuring predominantly *Cosmonotus* Crab, serve as alternative foraging areas during high tide (Aarif et al., 2021a).

Shorebirds of the CAF have drawn attention due to recent long-term reports on their steady declining population trends and altered diversity in wintering grounds (Shamna et al., 2023). Large-scale catastrophic declines in wintering shorebird populations have been reported from the east (Rashiba et al., 2022) and west coast of India (Aarif et al., 2021a). It was primarily due to changes in environmental variables and associated depletion of invertebrate prey items (Aarif et al., 2021a), and declining primary productivity (Athira et al., 2022). As the global populations of migratory shorebirds decrease, a key challenge is to determine whether short-term foraging benefits can reliably predict long-term fitness. Understanding the relationship between dietary habits, prey availability, and habitat use will provide insights into how environmental changes affect shorebird populations and species persistence.

Being the top-level predators in coastal ecosystems, they are highly vulnerable to environmental pollution owing to their unique migratory ecology and foraging

behaviour (Aarif et al., 2023). In India, a sizable portion of the human population resides close to the coasts, and the natural balance of coastal ecosystems has been disrupted by harmful anthropogenic contaminants released there over a long period of time. Shorebirds are sentinel species, which can provide an interpretation of pollution levels and a comprehensive measurement of all its impact on the ecosystem. Heavy metals and microplastics are the most concerning pollutants due to their potential to cause harmful effects on organisms and ecosystems.

Discarded plastics in coastal areas can directly harm organisms through entanglement and injury (Aarif et al., 2021b). Microplastics are commonly referred to plastic particles with a size smaller than 5 mm. They can be formed by the disintegration of larger plastics (Law & Thompson, 2014) or that are manufactured by industrialists for use in cosmetics or personal care products (Crawford & Quinn 2017). Microplastic contamination has been identified as a global issue but its mechanisms of action in triggering troubles in ecosystem structure and function have not yet been completely unravelled. Microplastic particles can reach a wide range of organisms by entering the food chain because they are found in all marine ecosystems, including sandy beaches, the coastal zone, the open ocean, and the deep sea (Carvalho Ferreira & Lôbo-Hajdu, 2023). Heavy metal pollution is also concerning due to their toxicity, intrinsic persistence, non-biodegradable nature, and accumulative behaviours (Ali et al., 2019).

This thesis, inspired by optimal foraging theory and the principle that 'in nature, everything is connected', investigates the interactions between shorebirds and their prey at critical wintering sites. It highlights how these complex dynamics, shaped by habitat changes and environmental stressors, influence both shorebirds and coastal ecosystems. By addressing key aspects of shorebird ecology and their responses to habitat changes, this study aims to provide a foundation for evidence-based conservation strategies.



OBJECTIVES

Objectives

- To compare the effectiveness of shorebirds' foraging techniques in selected habitats.
- To study the extent of habitat degradation and the adaptive foraging strategies of shorebirds along the west coast of India.
- To assess environmental pollution and its trophic transfer to shorebirds across diverse coastal ecosystems.

Study area

The Central Asian Flyway spans 30 countries across central Eurasian Continent (Kumar et al., 2020), a crucial flyway region providing essential non-breeding habitats for a vast number of migratory shorebirds. India serves as a critical wintering ground for shorebirds along the CAF. The west coast of India serves as stop-over sites, staging areas, wintering grounds and over-summering locations (Rashiba et al., 2022). The study was conducted in the coastal habitats and adjoining inland agroecosystems along the west coast of India (Figure 1). Kerala, situated along the southwest coast of the Indian peninsula and bordered by the Arabian Sea to the west, boasts an extensive coastline stretching approximately 590 km. A significant portion of this coastline lies in the northern region, constituting a quarter of Kerala's coastal expanse (Pavithran, 2021). Among the coastal habitats, the Kadalundi-Vallikkunnu Community Reserve (KVCR) is internationally recognized for its significant foraging grounds supporting both wintering and over-summering shorebirds (Aarif et al., 2011).

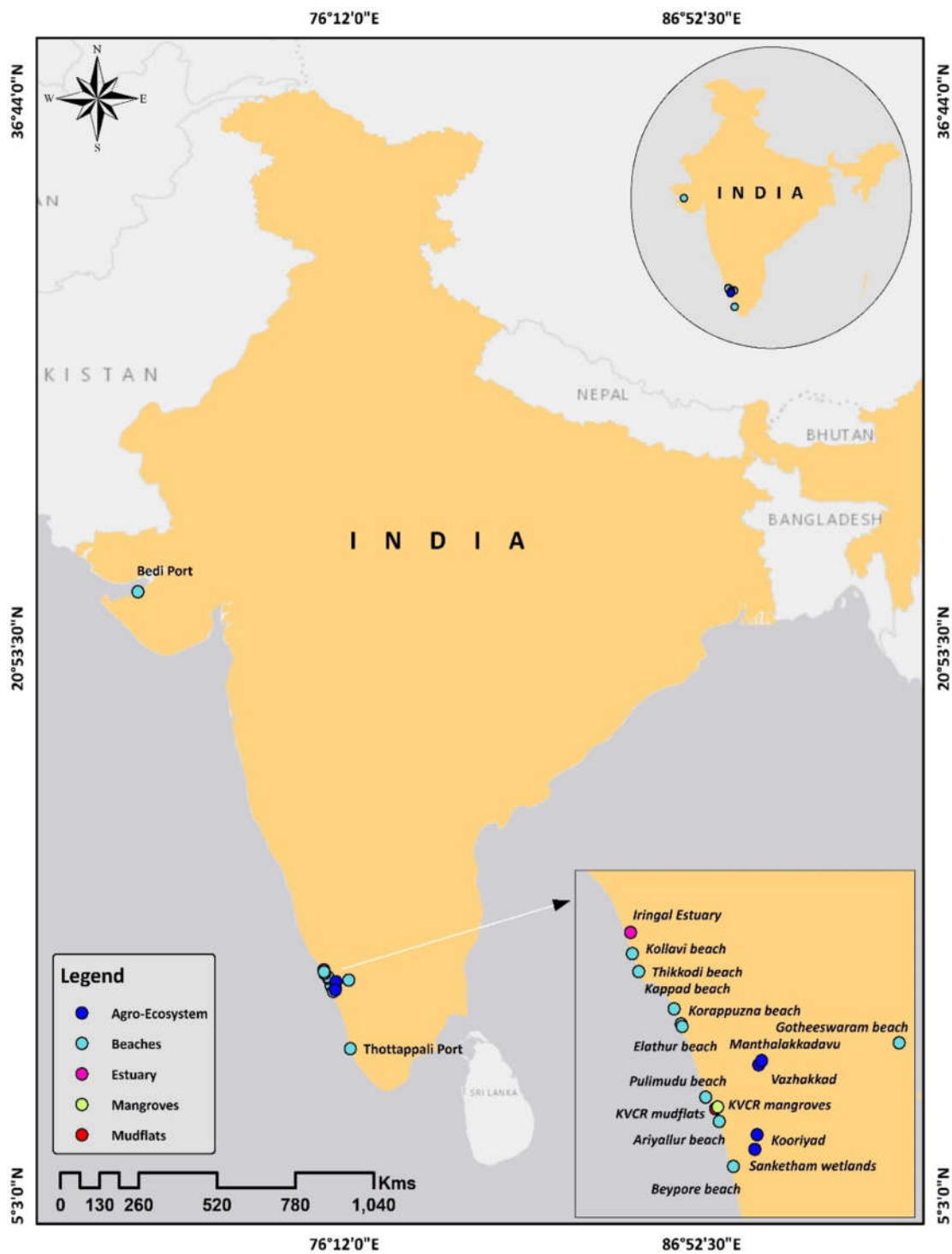


Figure 1. Map of the study area encompassing KVC mangroves, adjoining sand beaches, salt pan and agroecosystems along the west coast of India.

The Kadalundi-Vallikkunnu Community Reserve (KVCR) is one of India's four Community Reserves, situated, where the Kadalundi River meets the Arabian Sea along the west coast of India. The river diverges into two channels around a small island before reaching the sea. Sandbars on the island's western and southern sides separate the lagoon from sea. Besides scattered mangrove patches, the estuary is bordered by coconut groves and human settlements (Aarif et al., 2011, 2014). In the KVCR, two primary habitats are distinguished: mudflats and mangroves (Figure 2). During high tide, shorebirds utilize adjacent sand beaches, salt pans and agro-ecosystems as alternative roosting and foraging sites.

Mudflats

The Kadalundi mudflats (11°07'37.5"N 75°49'48.6"E) encompass an 8-hectare area exposed during low tides, providing a significant foraging habitat for various wintering and oversummering shorebirds (Aarif et al., 2014, 2020, 2021a; Rashiba et al., 2022). The vertical soil layers in this habitat are arranged as follows: the first 5 cm contain mud, the second layer contains mud with very fine sand, and the third layer, another 5 cm deep, contains mud with larger sand grains (Rubeena et al., 2023).

Mangroves

Mangroves are adjacent to mudflats, and it is the second most important foraging grounds for shorebirds in KVCR (Aarif, 2009). The mangrove forests are located on the eastern side of the mudflats. Seven species of mangroves viz.: *Sonneratia alba*, *Avicennia officinalis*, *A. marina*, *Rhizophora mucronata*, *Bruguiera cylindrica*, *Acanthus ilicifolius*, and *Excoecaria agallocha* dominate in KVCR. *Avicennia officinalis* is the predominant species. *Sonneratia alba*, a planted species, forms dense patches near the mudflats (Aarif et al., 2014). The mangroves serve as spawning, nursery, and feeding grounds for a diverse range of organisms, including fishes, crustaceans, molluscs and other invertebrates.



Figure 2. The exposed mudflats **(a)** and mangroves **(b)** of KVCR.

Sand Beaches

The present study sites also include sand beaches along the west coast of India: Ariyallur beach, Pulimudu beach, Beypore beach, Gotheeswaram beach, Korappuzha beach, Elathur beach, Kappad beach, Thikkodi beach, Iringal estuary, Kolavippalam (Kollavi) beach and Thottappalli beach (Figure 3). Ariyallur beach, located in Tirurangadi Taluk of Malappuram district, and Pulimudu beach, situated opposite Beypore port in Kozhikode Taluk of Kozhikode district, are approximately 7.36 km apart. These sandy beaches located roughly 1.5 km and 4.76 km from the Kadalundi-Vallikkunnu Community Reserve (KVCR), respectively, serve as alternative foraging grounds for shorebirds of KVCR during high tides (Aarif & Musammilu, 2018). Ariyallur beach features a boat landing site on its northern border and a Panchayath road on its southern border, adjacent to local settlements within the sampling area. Pulimudu beach, positioned at the estuary of the Chaliyar River across from Beypore Port, is noted as the most polluted beach in the area. Beypore beach (11°09'52.7"N 75°48'07.3"E) and Gotheeswaram beach (N 139 11°18'12.62" E 75°79'64.74") are situated about 8km and 13 km away from KVCR respectively along the northern side. Elathur beach, a less polluted sandy beach in Kozhikode Taluk of Kozhikode district, is bordered by the Arabian Sea in the west and Korappuzha river in the north and is approximately 33 km from KVCR. Korappuzha beach, located approximately 3.8 km from Elathur beach, is another sandy beach where the Korappuzha River empties into the Arabian Sea. Kappad beach, a rocky shoreline in Koyilandi Taluk, is about 25 km from KVCR and is recognized as one of the cleanest beaches along the west coast, with human settlements far from the sampling area. Iringal Estuary and Kolavippalam beach, located adjacent to each other in Koyilandi Taluk, are approximately 59 km from KVCR and have human settlements near the coast. Thikkodi beach, a drive-in beach in Vadakara Taluk, is approximately 51 km from KVCR. Thottappalli beach (9°18'35.7" N 76°22'54.6"E) is located in Purakkad, Alappuzha District and is Kuttanad's drain-way-out to the Arabian Sea.

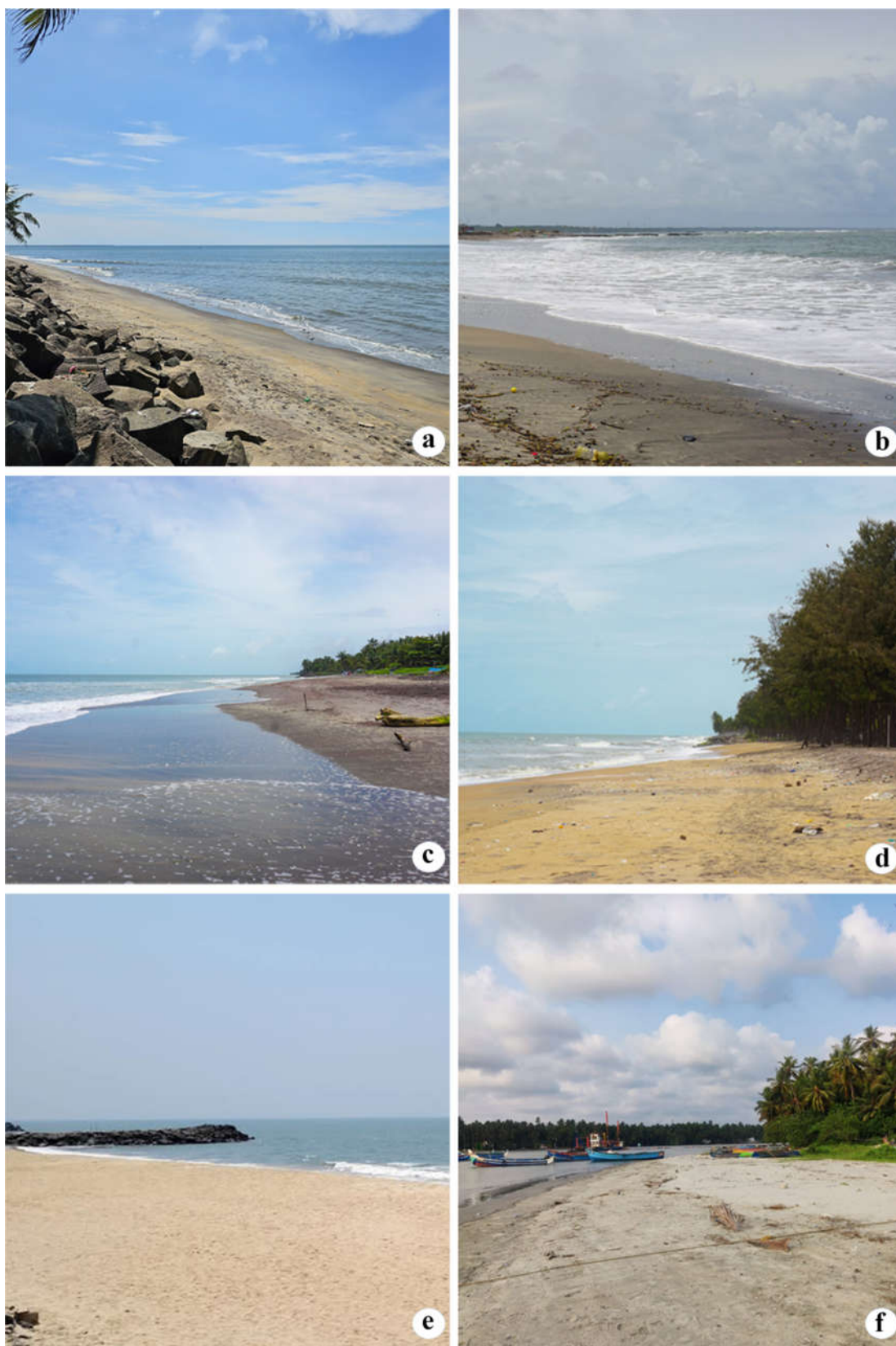




Figure 3. Selected sand beaches along the west coast of India. **(a)** Ariyallur beach, **(b)** Pulimudu beach, **(c)** Beypore beach, **(d)** Gotheeswaram beach, **(e)** Korappuzha beach, **(f)** Elathur beach, **(g)** Kappad beach, **(h)** Thikkodi beach, **(i)** Iringal estuary, **(j)** Kolavippalam (Kollavi) beach, and **(k)** Thottappalli beach.

Salt pan

Bedi port (22°32'29.1"N 70°02'05.1"E) (Figure 4), a hub of port-related activities, features two primary habitats: mangroves and salt pans, that provide important wintering and stop-over grounds for migratory shorebirds in the west coast of India (Byju et al., 2024).

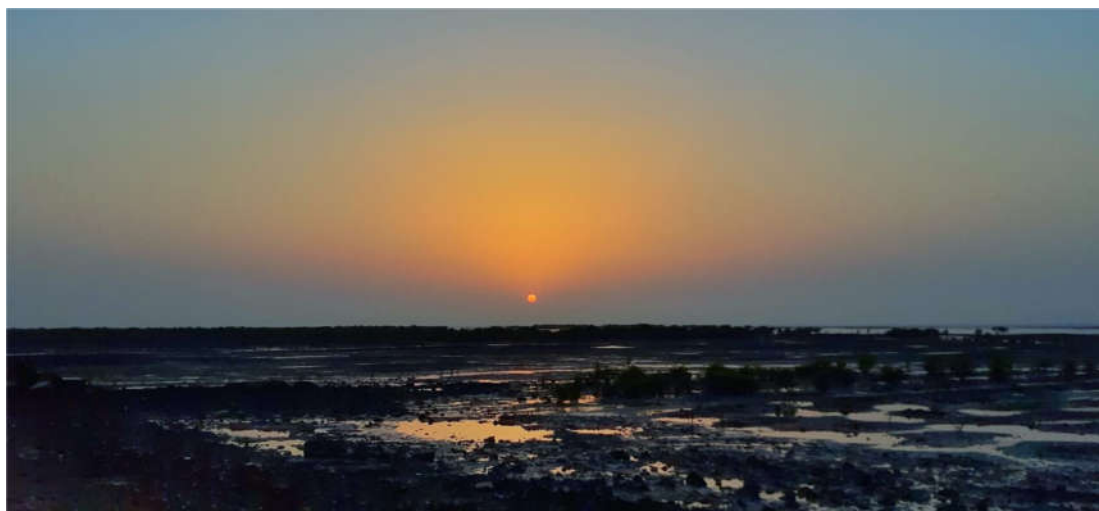


Figure 4. Bedi port salt pan along the west coast of India.

Agro-ecosystems

Vazhakkad (11°14'41.3"N 75°56'48.8"E), Kooriyad (11.0573664"N 75.9422234"E), Manthalakkadavu (11°15'20.8"N 75°57'17.3"E) and Sanketham wetlands (11°17'28.2"N 75°56'09.6"E) are the agroecosystems investigated (Figure 5). These sites are having seasonal paddy cultivation, situated in the vicinity of the KVCR and sand beach habitats. These agroecosystems were selected for study due to the observed transition of wintering shorebirds to these areas (Byju et al., 2024).

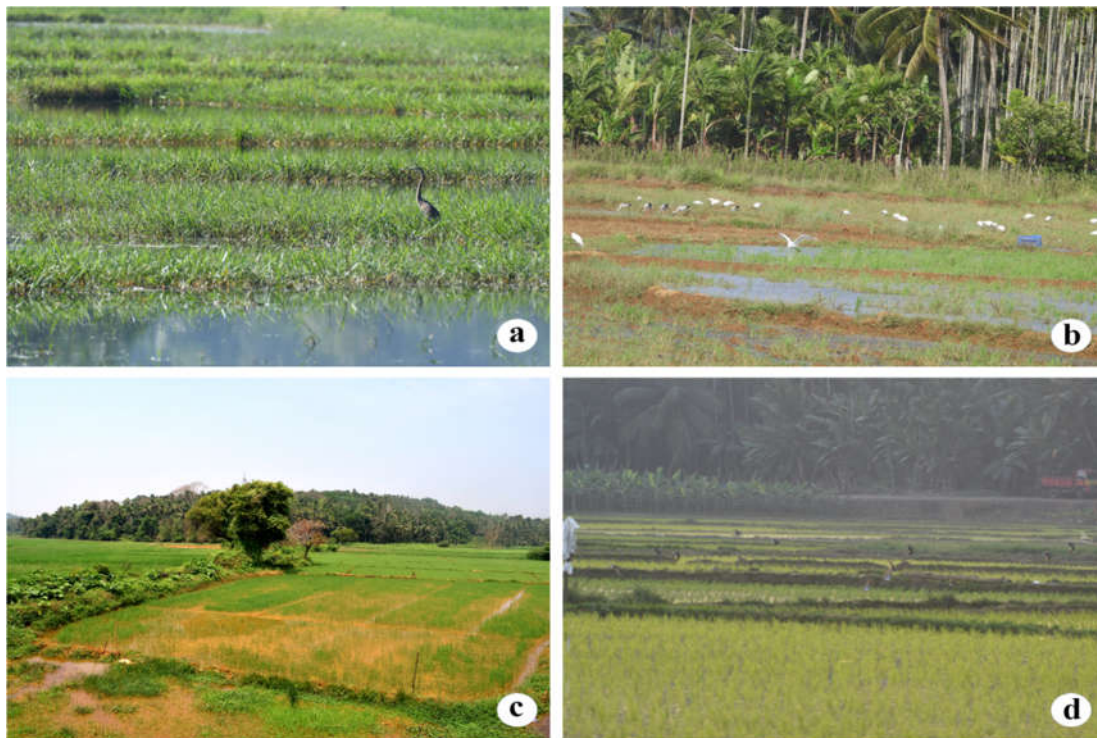


Figure 5. Selected agroecosystems along the west coast of India; **(a)** Vazhakkad, **(b)** Kooriyad, **(c)** Manthalakkadavu and **(d)** Sanketham wetlands.

Methodology

Species account

Migrant shorebirds, belonging to the families Scolopacidae and Charadriidae, with diverse foraging strategies were selected (Table 1, Figure 6). The species includes Eurasian Curlew (*Numenius arquata*), Black-tailed Godwit (*Limosa limosa*), Bar-tailed Godwit (*Limosa lapponica*), Whimbrel (*Numenius phaeopus*) Common Greenshank (*Tringa nebularia*), Common Redshank (*Tringa totanus*), Marsh Sandpiper (*Tringa stagnatilis*), Wood Sandpiper (*Tringa glareola*), Grey Plover (*Pluvialis squatarola*), Ruddy Turnstone (*Arenaria interpres*), Pacific Golden Plover (*Pluvialis fulva*), Sanderling (*Calidris alba*), Terek Sandpiper (*Xenus cinereus*), Greater Sand Plover (*Anarhynchus leschenaultii*), Tibetan Sand Plover (*Anarhynchus atrifrons*), Common Sandpiper (*Actitis hypoleucos*), and Kentish Plover (*Anarhynchus alexandrinus*) and Little Stint (*Calidris minuta*). They have diverse foraging strategies (Table 1). Eurasian Curlew, Black-tailed Godwit and Bar-tailed Godwit are designated as near threatened (NT) in the IUCN Red List (IUCN, 2024).

Table 1. Foraging mode and diet specialization of investigated shorebird species.

Species	Mode of foraging	Diet specialization
Kentish Plover	Epibenthic feeders	Benthic invertebrates in the upper sediment layer.
Tibetan Sand Plover		
Greater Sand Plover		
Pacific Golden Plover		
Grey Plover		
Ruddy Turnstone		
Common Sandpiper		
Common Redshank	Epi-meso-faunal benthic & Pelagic feeders	Benthic invertebrates in upper and medium depth sediment layer and water column. Zooplanktonic prey items via surface tension - based prey transport.
Common Greenshank		
Wood Sandpiper		
Marsh Sandpiper		
Terek Sandpiper		
Bar-tailed Godwit	Epi-meso-infaunal benthic feeders	Benthic invertebrates from upper, medium and deep layers of sediment.
Black-tailed Godwit		
Whimbrel		
Eurasian Curlew		
Sanderling	Epibenthic & biofilm feeders	Benthic invertebrates in the upper sediment layer, Biofilm grazing.
Little Stint		

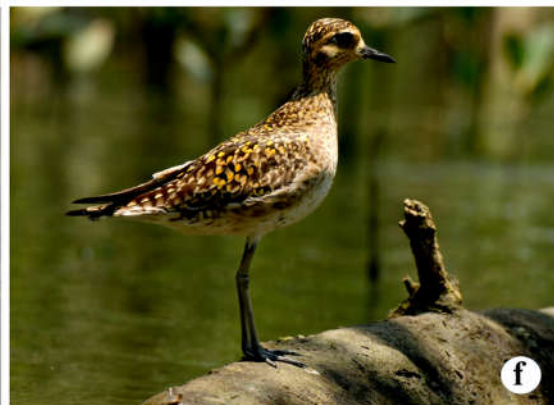






Figure 6. Selected species of shorebirds. **(a)** Kentish Plover, **(b)** Tibetan Sand Plover, **(c)** Greater Sand Plover, **(d)** Common Sandpiper, **(e)** Ruddy Turnstone, **(f)** Pacific Golden Plover, **(g)** Grey Plover, **(h)** Little Stint, **(i)** Sanderling, **(j)** Terek Sandpiper, **(k)** Wood Sandpiper, **(l)** Marsh Sandpiper, **(m)** Common Redshank, **(n)** Common Greenshank, **(o)** Bar-tailed Godwit, **(p)** Black-tailed Godwit, **(q)** Whimbrel, and **(r)** Eurasian Curlew.

(Species are arranged according to foraging strategy classification as presented in Table 1.)

Direct observation

Wintering populations of migratory shorebirds typically arrive on India's west coast, in the month of August and depart between March and May (Aarif et al., 2021a). Direct visual counts (Howes & Bakewell, 1989) were performed using binoculars (Nikon 10×50) and a spotting scope (Nikon 14×70) between 06:00 and 11:00 h, at fixed scanning points across the habitats. The observation was begun five minutes after arrival to the scanning point to allow shorebirds to acclimate to human presence (Aarif et al., 2020). Permanent scanning points were set up to conduct the surveys systematically. I have also recorded the number of shorebirds observed while moving from one scanning point to the next, treating these sightings as incidental records. The collected data were then analyzed to evaluate shorebird abundance along the surveyed beach sections. Video recording method was used to verify direct counts and to check for duplicate entries.

Video recording

The behavioural observation was made with help of 4K high speed motion latest video cameras (Sony CX 130 E and Nikon Coolpix p 1000 100 125 x optical zoom) in the selected study areas (Kuwaie et al., 2012). At each site, two observation points were established in different habitats (mudflats, mangroves, and sand beaches).

The bout was of 15 minutes duration and in between two successive bouts, 15 minutes gap was given. Care was taken to avoid maximum pseudo-replication by focusing on individually foraging birds rather than entire flocks and each bird focused was at least 25 m apart. Wintering shorebird data were collected during various post-monsoon months (October, November, December, January, February & March) and over-summering data was collected weekly during the monsoon period between 1 June to 15 July. During over-summering data collection, since observing with binoculars and spotting scopes was challenging under wet conditions, used count data from video recordings only to determine shorebird abundance. While not all scanning points were covered during each visit or every month, observations was based on the availability of the shorebirds in the vicinity of each scanning point. The recorded videos were played and replayed to verify the shorebird counts and to accurately assess the foraging behaviour, prey type, prey capture rates and foraging depth preferences (Kuwae et al., 2008). Species identification was confirmed with Message and Taylor (2005).

The number of actively foraging individuals in each habitat was recorded and used to assess feeding abundance. Capture rates were calculated as the number of prey items successfully captured by an individual shorebird per minute (Navedo et al., 2012). Foraging depth was categorized based on their depth of substrate penetration during prey capture. Superficial foraging was identified as probing close to the surface (about 1-3 cm), medium probing was identified by the partial immersion of bill into the sediment (3-6 cm) and deep probing was observed when birds fully insert their bill into the sediment (-15 cm) (Yu et al., 2023). I have used a field guide (Grimmett et al., 1999) and expertise from researchers with 18 years of experience in shorebird ecology to determine the age of individual bird. Adult and immature shorebirds were distinguished by their plumage characteristics. Particularly, the partial prealternate moult of adults into bright breeding plumage facilitates their differentiation from immature shorebirds (Tavera et al., 2020).

Diet spectrum through droppings analysis

To investigate the diet of shorebirds, observations on single-species flocks were conducted and collected their droppings, each preserved individually in 70% ethanol for subsequent analysis. The droppings were scrutinized under magnification ranging from $\times 10$ to $\times 400$, with the objective of identifying various structures such as fragments of mollusk shells, polychaete mandibles, and remnants of crustaceans and aquatic insects (Dekinga & Piersma, 1993). Any undigested prey remains were then classified to the most precise taxonomic category feasible, employing criteria drawn from pertinent literature sources (e.g., Bond-Buckup et al., 2009; Montú & Goeden, 1986). The dietary composition of shorebirds was determined based on the frequency of occurrence, defined as the proportion of droppings containing a specific prey taxon.

Estimation of water physical parameters

Water physical parameters including water temperature and salinity were estimated on a monthly basis using a digital salinity meter (Thomas@Traceable salinity meter, Japan) and pH using a digital pH meter (VIVOSUN pH and TDS Meter Combo). The nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations were also estimated following the American Public Health Association Manual (APHA, 2005). The Cadmium Reduction technique was used to determine NO_3^- concentrations, where the maximum reduction efficiency was $\geq 95\%$ during the experimental period. Molybdate-spectrophotometric method was used to determine PO_4^{3-} concentration. NO_3^- samples were run through spectrophotometer (UV-Visible Spectrophotometer, Thermo Scientific Evolution 201), while Molybdate-Spectrophotometer were used for PO_4^{3-} samples. Rainfall data were acquired from the Centre for Water Resources Development and Management (CWRDM) in Kozhikode, Government of Kerala.

Surface water samples were collected on a monthly basis during low tide from each location for nutrients, primary productivity (chlorophyll-a) and zooplankton

determination. The collected 1 L water was composed of four replicates (250ml x 4) of adjoining areas of each study sites at an average depth of 1-1.5 m.

Chlorophyll-a estimation

Water samples were collected on a monthly basis from each study site before sunrise using 1 Litre amber bottles. They were kept in the dark to avoid any light exposure until further use for the estimation of chlorophyll-a using the method indicated by Dere et al. (1998).

The water samples were filtered through 4.5 cm diameter GF/C glass filter paper with a thin bed of magnesium carbonate suspension (2ml) along with the action of a suction unit. After filtration, the filter paper along with the pigments was then crushed with 90 % acetone (10 ml). The supernatant obtained after centrifugation (500 x g for 20 minutes) was transferred to a cuvette (10 ml) and then the absorbance was measured in a spectrophotometer (UV-Visible Spectrophotometer, Thermo Scientific Evolution 201) at three wavelengths (630 nm, 645nm and 665nm) with a path-length of 10 cm. The chlorophyll-a ($\mu\text{g/L}$) content was estimated using the following equation,

$$\text{Chlorophyll-a} = 11.6 E_{665} - 1.31 E_{645} - 0.14 E_{630}$$

Where, E stands for the extinction (absorbance or optical density) at different wavelengths.

Estimation of zooplankton density

Twenty liters of surface water, bimonthly collected from each habitat, was filtered through a plankton net with a mesh size of 200 μm and the total planktonic abundance was estimated by hand picking method before transferring into film bottles which is then fixed and preserved in 4% formaldehyde in the laboratory for the taxonomic job (Sarker et al., 2016).

Water sampling (microplastic analysis)

A total of 70 seasonal water samples (seven samples/season/site) were collected throughout the pre monsoon (Feb-May), monsoon (June- Sep), and post monsoon (Oct- Jan) seasons from June 2020 to June 2022. For each season, 1 L of surface water samples from each habitat was collected utilizing a stainless-steel mug from 0-15 cm depth. The samples were then transferred to 1 L sterilized, labelled glass bottles and stored in a freezer at -20°C until further laboratory processing (Athira et al., 2024a).

Sediment sampling (microplastic analysis)

Seasonal sediment samples (seven samples/season/site) were collected from each habitat to a depth of 5 cm to capture microplastics deposited by the most recent tide, located in the uppermost section of the sediment layer. For each season, 250 g of sediment were collected using a stainless-steel scoop, transferred to labelled glass containers, and stored at -20°C until further processing (Athira et al., 2024a).

Biofilm sampling (microplastic analysis)

Biofilm samples were collected (one-time sampling) from mudflat and mangroves sediments, where congregations of small shorebirds were regularly observed as foraging. Biofilm presence was confirmed based on visual inspection and field expertise. The top ~2 mm layer of sediment from 10 cm circular plots at each site was gently extracted using a stainless-steel spatula, then transferred into sterilized glass vials after removing any visible macroinvertebrates (Aarif et al., 2023). The samples were stored at -20°C until further analysis.

Phytoplankton and zooplankton sampling (microplastic analysis)

Surface water (20 L) was collected from mudflats and mangroves, then filtered through plankton nets with a 200 µm mesh for zooplankton, followed by a 40 µm mesh for phytoplankton (one-time sampling). Plankton were immediately collected from the nets using a sterile natural fibre brush, washed with distilled water, and transferred to labelled glass bottles. The samples were then stored at -20°C without preservatives until further processing.

Prey sampling (abundance and microplastic analysis)

The prey abundance sampling was done once a month during low tide between 2020 and 2022 at mudflats, mangroves, and sand beaches. Macrobenthic invertebrates including polychaetes (*Ceratonereis burmensis*, *Heteromastus filiformis*) and crabs (*Dottilla myctiroides*) were collected (one-time sampling) from mangroves and mudflats while Cosmonotus crabs (*Emerita holthuisi*) were collected from sand beaches. They were sampled during low tide hours, using a 10 cm diameter metallic cylinder at a depth of 15 cm. Two sampling points were chosen at each site based on the highest densities of foraging shorebirds, ensuring minimal disturbance (Aarif et al. 2021a). A total of three replicates of each species were collected. The collected prey items were washed with distilled water to remove adhering sediments. Shrimps (*Metapenaeus dobsoni*) were captured by sweeping 200 µm mesh nets in the water columns of mudflats. All samples were transferred to separately labelled glass bottles and stored at -20°C.

Shorebird droppings sampling (heavy metal and microplastic analysis)

Droppings samples were collected from two scanning points within both mudflats and mangroves of KVCR, and from a single point on each of the adjacent sand beaches. Site selection was based on shorebird abundance. At the mudflats and mangroves, sampling was conducted during receding tides, with collection times varying between 8.00 - 17.00 hrs, depending on tidal dynamics. Monitoring of shorebird behaviour was conducted using high-resolution 4K video cameras (Nikon Coolpix P1000, D500 Nikon DSLR with 200-600mm telephoto lens), ensuring accurate species identification throughout the sampling period. Sample collection focused on individual birds to avoid maximum pseudo-replication. The sampling covered ten shorebird species, including the IUCN near-threatened Eurasian Curlew (*Numenius arquata*) and Bar-tailed Godwit (*Limosa lapponica*). The other species included were Common Greenshank (*Tringa nebularia*), Common Redshank (*Tringa totanus*), Whimbrel (*Numenius phaeopus*), Sanderling (*Calidris alba*), Greater Sand Plover (*Anarhynchus leschenaultii*), Tibetan Sand Plover (*Anarhynchus mongolus*), Common Sandpiper (*Actitis hypoleucos*), and Kentish Plover (*Anarhynchus*

alexandrinus). Species were confirmed with the help of field guide Message and Taylor (2005). Fresh droppings were collected immediately after observing defecation from the targeted shorebird, using sterile stainless-steel spatulas to avoid contamination. Sample collection was more efficient at the mudflats, where abundant feeding opportunities after receding tides facilitated rapid sample gathering. Collection at the sand beaches took longer due to wave disturbances and slower foraging behaviours.

The samples were collected and preserved in labelled sterilized glass vials. A large number of samples were collected to facilitate the exclusion of those with insufficient quantities. A total of 170 droppings samples were collected for heavy metal analysis across the three habitats: 45 samples from the mudflats, 45 from the mangroves, and 50 from the sand beaches. For microplastic analysis, a subset of 30 samples was selected from the entire collection, with three replicates utilized per species. All samples were immediately frozen at -20°C upon collection and were stored under these conditions until laboratory analysis. Three replicates per species were used for microplastic analysis, while five replicates per species were employed for heavy metal analysis to ensure reproducible results (Aarif et al., 2023, 2024).

Heavy metal analysis

The droppings samples for evaluation of heavy metals were weighed and transferred aseptically to tetrafluorometoxil polymer bomb vessels, and subsequently, 9 ml of HNO₃ (Merck) was added to each sample and subjected to high-pressure, high-temperature microwave Digestion (Titan MPS, Perkin-Elmer, USA). Post-digestion, samples were diluted to 20 mL with acidified water (Aarif et al., 2023).

All the prepared samples were analysed for the following heavy metals by Flame Atomic Absorption Spectrophotometer (PinnAAcle 500, Perkin-Elmer, USA): Cadmium (Cd), Cobalt (Co), Chromium (Cr), Lead (Pb), Zinc (Zn) and Copper (Cu). The operating wavelengths for these elements were 228.80 nm, 240.73 nm, 357.87

nm, 283.31 nm, 213.86 nm and 324.75 nm for Cd, Co, Cr, Pb, Zn and Cu respectively (Rajaram et al., 2017). Electrodeless discharge lamp (EDL) was employed in AAS to improve the sensitivity and lower detection limits. This method also provides optimized spectral output needed to get maximum performance for the elements- Cd and Zn (Ganeev et al., 2003). The sample preparation, processing and analyses were carried out in a sterile and aseptic condition to rule out any chances of contamination.

Microplastic analysis

Water samples were individually processed using 500ml of 10% of Potassium hydroxide solution (KOH) at room temperature for digestion of organic matter over a span of two days to one week. This approach is recognized for efficiently degrading organic material while preserving the integrity of microplastic particles (Aguirre-Sanchez et al., 2022). For each sediment sample, 250 ml of 10% KOH was added with continuous stirring to ensure even digestion (Besley et al., 2017). This process was repeated until a total of 1 L of KOH solution had been added, occasionally stirring over 5 - 10 days until all organic material was fully digested. The volume was adjusted as necessary to ensure complete digestion. After allowing the sand particles to settle, the supernatant was collected and filtered it using glass microfiber filters. The biofilms and plankton samples were also treated separately with 50 ml and 25 ml of 10% KOH solution respectively for 2-4 days. Since a 10% KOH solution is known to dissolve a range of tissues (Geppner et al., 2023), all the prey samples were also treated with the same solution in volumes ranging between 500 ml- 750 ml for 4-5 days. The shorebird's droppings samples were also treated with 500 ml of 10% KOH solution for 4-5 days with occasional stirring with a glass rod.

Following the digestion of organic material, water, sediment, and other samples were filtered through 1 μ m glass microfiber filters under vacuum. These filters were then placed in petri dishes, and the dried samples were examined under a stereo-zoom microscope (Leica MSV266 Stereo-Zoom Microscope). Microplastics were

identified by possessing unnatural coloration (e.g., blue, green/ black, red, white) (Hidalgo-Ruz et al., 2012), and were confirmed using a *hot needle test* (Beckingham et al., 2023). The characteristics including quantity, shape, colour, and size of particles were recorded manually and images were taken with a Leica camera (DMC2900) attached to the microscope. Microplastics were categorized into size categories less than 1 mm, 1–2 mm, 2–3 mm, 3–4 mm, and 4–5 mm. Polymers were identified using attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR). Samples on filter papers were scanned over a frequency range of 4000-400 cm^{-1} , with data acquisition at a resolution of 4 cm^{-1} . The spectra obtained were then compared with reference spectra from previous studies to determine polymer types.

Quality analysis and quality control (heavy metal and microplastic analysis)

The quality assurance and quality control throughout the procedures and analyses were maintained by running QC samples at regular intervals for the accuracy in the heavy metal assessment and thus to ensure the stability of the equipment. The standard solutions supplied by the Perkin-Elmer were used to prepare calibration curves for each metal and limits of detection. For non-hazardous heavy metals, the detection limits were 0.004 mg/kg for Zn, 0.002 mg/kg for Cu and 0.01 mg/kg for Co. The detection limits for hazardous metals were 0.001 mg/kg for Pb, Cr and Cd. For ensuring the accurate measurement of samples, the equipment was calibrated using blank samples. All the chemicals and reagents used were purchased from Merck (Germany) and the glassware were washed thoroughly and rinsed with deionized water and later acidified water.

Microplastic analysis is susceptible to contamination from airborne particles posing a significant challenge to data quality assurance (Prata et al., 2021). Microplastics may be found in reagents used for digesting organic matter, laboratory equipment, the laboratory environment, and both distilled and ultra-pure water (Prata et al., 2021). The sampling and experimental procedures were conducted with strict measures to prevent cross-contamination. Glass and stainless-steel equipment were utilized for sampling, preservation, alkaline digestion, and filter analysis.

Apparatus and glassware were rinsed with distilled water and filter paper was pre-rinsed with 1 μm organic filter paper. 10% KOH solution was filtered through 1 μm GF/A filter papers before use. The workstation was sanitized with 70% ethanol, and the filter papers were examined under a microscope for airborne contaminants prior to use. After filtration, the filter papers were stored in glass Petri dishes with lids, which had been rinsed with prefiltered distilled water. All procedures and observations were conducted promptly to ensure accuracy.

Challenges of microplastics analysis

The dynamic nature of coastal environments can affect the representativeness of water and sediment samples collected. Complexity involved in sample preparation and prevention of contamination is a significant challenge for reliable detection of microplastics. Achieving uniform digestion of organic matter in sediment samples without stirring also posed challenges. Although stirring was essential to ensure even and proper digestion, it could potentially lead to airborne contamination. Furthermore, the manual quantification of microplastic particles is largely time-consuming and prone to pseudo-replication due to the presence of natural debris resembling microplastics.

Statistical Analysis***Chapter 1***

To test the effect of the seven predictors (time duration (minute), year, month, microhabitat type (mudflats, mangroves, sand beaches), sex (male, female, unknown), foraging depth (Deep, Medium, Superficial), and shorebirds (Bar-tailed Godwit, Eurasian Curlew) on each one of responses variables (total prey consumed and capture rate) separately, performed a GLM using the “glm” function. This provided a good fit after checking for overdispersion, heterogeneity residual patterns, and non-linearity. Microhabitats, sex, species, time duration, and deep foraging were used as independent variables. The analyses were performed using R-3.0.2 software (R Core Team, 2013). I have used the 'vegan' package to calculate ecological indices, and the 'MASS' and 'lme4' packages to apply generalized linear mixed models (Fox & Weisberg, 2019). The 'ggplot2' package was used to plot the relationship between foraging success and total prey consumed separately with explanatory variables included in the best models.

The effects of explanatory variables which are: 1) site (Ariyallur, Kappad, Pulimoodu), 2) Month (January, February, March, October, November, December), 3) year (2016, 2017, 2018, 2019, 2020, 2021, 2022) and 4) Foraging technique (straight-line, zigzag) on the “capture success” (refer “behavioural data analysis” section), as response variable were analyzed using Generalized Linear Mixed Model (Gaussian error with identity link), with site and month nested in years as random effect.

Collinearity between explanatory variables was checked using a Variance Inflation Factors (VIF) that quantifies the extent of increase in the variance arising out of collinearity of multiple explanatory variables (James et al., 2013). Variables with a $VIF \geq 5$ were not accepted (Hair et al., 1995). No individual covariate exceeded 5 in the final matrix; hence each explanatory covariate was retained (Table 2). Interactions between predictors were included.

Table 2. Variance Inflation Factors (VIF) to check for multicollinearity of variables used in the models explaining the capture success.

Effect	Level of effect	Tolerance	VIF	R ²
Year	2016	0.7113	1.4057	0.2886
Year	2017	0.7132	1.4019	0.2867
Year	2018	0.8980	1.1134	0.1019
Year	2019	0.8579	1.1656	0.1420
Year	2020	0.8971	1.1147	0.1028
Year	2021	0.8099	1.2346	0.1900
Month	January	0.3678	2.7187	0.6321
Month	February	0.3482	2.8712	0.6517
Month	March	0.3530	2.8321	0.6469
Month	October	0.2890	3.4594	0.7109
Month	November	0.3738	2.6746	0.6261
Site	Ariyallur	0.6166	1.6217	0.3833
Site	Kappad	0.6209	1.6104	0.3790
Foraging technique	Zigzag	0.9321	1.0728	0.0678

Akaike's Information Criterion (AIC) values were used to rank and select the model of best fit (Burnham & Anderson 2002). The Akaike Weight of each model was calculated to determine the strength of explanatory variables on response variables. The Chi square (X^2) test was used to evaluate the association between the used foraging behaviour (Two categories: zigzag or straight-line) and prey categories captured (Five categories: Cosmonotus crabs, Crabs, Bivalves, Prawn and Aquatic insects). The statistical analyses were conducted in Statistica 12.0 software (Stat Soft Inc., 2013).

The frequency of occurrence (%FO) was estimated for each prey item, expressed as the percentage of total samples in which a particular food item was recorded. This parameter provides a standardized measure of how common each prey item is in the diet, expressing the number of individuals that have consumed a particular prey (e.g. Lourenço et al., 2017; Angarita-Báez & Carlos 2023b). To assess differences in shorebird diet, Non-metric Multidimensional Scaling (NMDS) was employed. This multivariate statistical technique is used to represent proximity

relationships between a set of objects in a lower-dimensional space, typically two dimensions, for visualization and interpretation. In NMDS the stress value is a statistical measure that indicates how well the ordination represents the original distances between samples, and lower stress values are generally considered better (<0.2). The results of NMDS are presented in a graph where each object is represented as a point in the lower-dimensional space. The proximity between points in the graph reflects the similarity between objects based on the original variables. Distance is measured using the Bray-Curtis index, where values close to 0 indicate greater dissimilarity, while values closer to 1 indicate greater similarity. The index is calculated by summing the absolute differences in species abundance between the two samples (Dexter et al., 2018). To provide a more intuitive understanding of the results, the Bray-Curtis similarity values were transformed into percentages by multiplying by 100. The 'MASS' package (Venables & Ripley 2002) was utilized to calculate the indices and the 'ggplot2' package (Wickham, 2016) to visualize the relationships between habitats, species, and prey consumed. All statistical analyses were conducted in R software (R Core Team, 2023)

One-way ANOVA was conducted to evaluate the variation in the abundance of both Bar-tailed Godwit and Eurasian Curlew across the years (2010-2023) and among different habitats (mudflats, mangroves and sand beaches). Following significant findings in ANOVA, Post-hoc analysis was conducted using Tukey's HSD test to determine habitat-specific variability. Pearson's Chi-squared test was conducted to determine the association between consumed prey type and habitat and between prey type and shorebird species. For the prey types exhibited significant association, pairwise comparisons were conducted using Bonferroni correction for multiple testing. These statistical analyses were performed using R 4.4.1 (R Development Core Team, 2014).

Chapter 2

One Way ANOVA was conducted on the mean values of Rainfall, water temperature, water salinity, water pH, water nitrate, water phosphate and chlorophyll-a to determine annual trends. The effect of years, seasonality, habitat structure, and water characteristics on the variation of zooplankton abundance was tested using Generalized Linear Mixed Models GLMMs (Gaussian error with identity link). Collinearity between explanatory variables was checked using a Variance Inflation Factors (VIF) that quantifies the extent of increase in the variance arising out of collinearity of multiple explanatory variables. Variables with a $VIF \geq 10$ were not accepted (Hair et al., 1995). No individual covariate exceeded this threshold in the final matrix; hence each explanatory covariate was retained (Table 3). To avoid complex models, the interactions between predictors were not included in the analysis. The effects of habitat, seasonality, rainfall, water temperature, water salinity, water pH, water phosphate and chlorophyll-a were examined as explanatory variables influencing zooplankton abundance with habitat included as a random effect. The Akaike's Information Criterion (AIC) values were used to rank and select the model of best fit (Burnham & Anderson, 2002) with the lowest AIC and highest AIC weight value for zooplankton abundance as response variables being that containing the most significant explanatory variables, since $n/k > 40$ for all models. The n indicates number of observation and k indicate number of parameters. The Akaike Weight of each model was calculated to determine the strength of explanatory variables on response variables. All statistical analyses were conducted in Statistica 12.0 software (Stat Soft Inc., 2013).

Table 3. Variance Inflation Factors (VIF) to check for multicollinearity of variables used in models explaining zooplankton abundance variation.

	Level of effect	Tolerance	VIF	R ²
Water Temperature		0.2614180	3.8252910	0.7385820
Water Salinity		0.4770540	2.0961987	0.5229460
pH		0.4482406	2.2309446	0.5517594
Water Phosphate		0.1757207	5.6908500	0.8242793
Chlorophyll a		0.4741820	2.1088948	0.5258180
Habitat	Mudflats	0.2799995	3.5714350	0.7200005
Habitat	Mangroves	0.2401291	4.1644273	0.7598709
Season	Dry	0.5651764	1.7693591	0.4348236
Year	2010	0.2860254	3.4961934	0.7139746
Year	2011	0.3242589	3.0839552	0.6757411
Year	2012	0.3575705	2.7966509	0.6424295
Year	2013	0.3962149	2.5238828	0.6037851
Year	2014	0.4269728	2.3420698	0.5730272
Year	2015	0.4617960	2.1654583	0.5382040
Year	2016	0.4958674	2.0166681	0.5041326
Year	2017	0.5180665	1.9302542	0.4819335
Year	2018	0.5411324	1.8479765	0.4588676
Year	2019	0.0000000		

A chi-square test was performed to examine the categorical data collected from observations of foot trembling incidents. The analysis was run using Statistica 12.0 software (Stat Soft Inc., 2013). Visualizations of the data were generated using Python 3.12.0.

The trend of shorebird abundance and diversity across years, habitat types and species were analysed by fitting general linear mixed models (GLMM). For the GLMM for diversity (Gaussian error with identity link), the response variable “diversity (expressed as Shannon index)” was modelled as a function of year (2016, 2017, 2018, 2019, 2020, 2021, 2022 and 2023), and included the habitat type (Mudflats, Salt pan, Sand beaches and Agricultural land) as random intercepts. Thereby, for the GLMM for abundance of shorebirds (with Poisson distribution error (count data)), the response variable “abundance” was modelled as a function of

year and included the habitat type and species identity (13 over summering shorebird species) as random effects.

Table 4. Variance Inflation Factors (VIF) to check for multicollinearity of variables used in models explaining abundances and diversity of shorebirds.

Response variable	Explanatory variables	Level of effect	Tolerance	VIF	R ²
Abundance of shorebirds	Year	2016	0.5714	1.7500	0.4285
	Year	2017	0.5714	1.7500	0.4285
	Year	2018	0.5714	1.7500	0.4285
	Year	2019	0.5714	1.7500	0.4285
	Year	2020	0.5714	1.7500	0.4285
	Year	2021	0.5714	1.7500	0.4285
	Year	2022	0.5714	1.7500	0.4285
	Habitat type	Mudflats	0.2845	3.5143	0.7154
	Habitat type	Sand Beaches	0.3257	3.0697	0.6742
	Habitat type	Salt pan	0.2690	3.7169	0.7309
	Species	Tibetan Sand Plover	0.8850	1.1299	0.1149
	Species	Whimbrel	0.8076	1.2381	0.1923
	Species	Greater Sand Plover	0.8076	1.2381	0.1923
	Species	Pacific Golden Plover	0.6708	1.4906	0.3291
	Species	Ruddy Turnstone	0.8076	1.2381	0.1923
	Species	Common Redshank	0.8733	1.1450	0.1266
	Species	Common Greenshank	0.7783	1.2847	0.2216
	Species	Black-tailed Godwit	0.7845	1.2745	0.2154
	Species	Marsh Sandpiper	0.8324	1.2012	0.1675
	Species	Common Sandpiper	0.7845	1.2745	0.2154
	Species	Little Stint	0.6895	1.4501	0.3104
	Species	Grey Plover	0.6589	1.5175	0.3410
Diversity of shorebirds	Year	2016	0.5714	1.7500	0.4285
	Year	2017	0.5714	1.7500	0.4285
	Year	2018	0.5714	1.7500	0.4285
	Year	2019	0.5714	1.7500	0.4285
	Year	2020	0.5714	1.7500	0.4285
	Year	2021	0.5714	1.7500	0.4285
	Year	2022	0.5714	1.7500	0.4285
	Habitat type	Mudflats	0.9333	1.0714	0.0666
	Habitat type	Sand beaches	0.9333	1.0714	0.0666
	Habitat type	Salt pan	0.9333	1.0714	0.0666

The shorebird diversity by Shannon diversity index (DeJong, 1975) was measured monthly, calculated in each field count attempt of each year in each habitat type.

Collinearity between explanatory variables was checked using a Variance Inflation Factors (VIF) that quantifies the extent of increase in the variance arising out of collinearity of multiple explanatory variables (James et al., 2013). Variables with a $VIF \geq 5$ were not accepted (Hair et al., 1995). No individual covariate exceeded 5 in the final matrix; hence each explanatory covariate was retained (Table 4).

Akaike's Information Criterion (AIC) values were used to rank and select the model of best fit (Burnham & Anderson 2002). The Akaike Weight of each model was calculated to determine the strength of explanatory variables on response variables. All statistical analyses were conducted in Statistica 12.0 software (Stat Soft Inc., 2013).

Chapter 3

To determine which combination of microplastic size ranges best accounted for variability among the water and sediment samples and the prey and shorebird droppings samples, network analysis was conducted using package network (Butts, 2015) and the visualization using igraph (Csardi & Nepusz, 2006). PCA (Principal Component Analysis) was carried out using ade4 package (Bougeard & Dray, 2018). Graphics were generated with factoextra (Kassambara & Mundt, 2020).

PCA (Principal Component Analysis) was carried out using ade4 package (Bougeard & Dray, 2018) to determine the patterns of occurrence of heavy metal in the selected ten species of shorebirds. A two-way ANOVA was conducted using Python 3.12.0 software, to evaluate the variation in heavy metal concentration across different habitats and species. Following significant findings in ANOVA, post-hoc analysis was conducted using Tukey's HSD test to determine habitat-specific variability. Graphics were generated with factoextra (Kassambara & Mundt, 2020). Circlize package (Gu, 2014) was used to generate the circular visualizations of the data.

A one-way ANOVA was conducted to evaluate variations in microplastic concentrations (response variables) across water and sediment samples, incorporating years (2020, 2021, and 2022) and seasons (monsoon, post-monsoon, and pre-monsoon) as covariates. Statistical analyses were conducted using Python 3.12.0 software. A generalized linear model (GLM) using a Poisson distribution with a log link function was utilized to analyse the abundance of prey, and the abundance of shorebirds in relation to various factors such as year, season, and primarily the abundance of microplastic. Prey abundance and shorebird abundance were the response variable and microplastic concentration in prey items was the predictor variable. The model selection was based on Akaike's Information Criterion (AIC), to rank and identify the best fit model based on the lowest AIC value (Burnham & Anderson 2002). AIC function was applied, and Akaike weights were calculated for each model to assess the influence of explanatory variables on response variables. R statistical software version 4.3.1 (R Core Team, 2023) was used for these statistical analysis.



CHAPTER 1

COMPARING THE EFFECTIVENESS OF SHOREBIRDS' FORAGING TECHNIQUES IN SELECTED HABITATS

Introduction

Shorebirds undertake some of the longest migrations known and are experiencing significant population declines globally (Aarif et al., 2014, 2017; Shamna et al., 2023; van de Pol et al., 2024). Migratory shorebirds (Charadriiformes) inhabit various habitats and demonstrate a broad spectrum of behavioural and ecological adaptations (Koleček et al., 2021; Wang et al., 2022; Angarita-Báez & Carlos, 2023b). They serve as crucial global indicators for assessing the health of delicate coastal ecosystems (Mathot et al., 2018; Sutherland et al., 2012). Most of them are apex predators in coastal ecosystem, playing a significant role in top-down regulation of prey populations, which can have cascading effects across multiple trophic levels and influence ecosystem processes (Hamilton et al., 2006; Mathot et al., 2018). Understanding their foraging behaviours provide insights into prey availability and overall ecosystem health (Mathot et al., 2018).

Historical review

Many shorebird populations are experiencing rapid declines due to multiple stressors, including habitat loss, climate change and prey depletion (Aarif et al., 2021a). During the non-breeding season, they rely on some coastal, estuarine or inland wetlands as their staging or wintering grounds after long-distance migration. This season is particularly critical, as it directly influences their survival and reproductive success (Marra & Holmes, 2001; Jourdan et al., 2021). Therefore, foraging is the major activity of shorebirds at their stop-over and wintering sites (Sampath et al., 1995) and Inorder to meet their higher energy demands, shorebirds must adopt efficient foraging strategies (Zhao et al., 2017). Foraging success rate plays a crucial role in the geographical distribution, habitat selection, migration and reproductive success of shorebirds (Athira et al., 2024c). The ongoing extinction risk faced by shorebirds underscores the necessity of a deeper understanding of their feeding ecology during this crucial period.

The optimal foraging theory suggests that foraging decisions are based on a maximization of currencies (Stephens & Krebs 1986; Ydenberg & Hurd 1998; Bautista et al., 2001). Accordingly, the profitability of prey is determined by a trade-off between handling costs (time, energy & predation) and gross energy gain, influenced by factors such as prey size, nutritional quality and digestability (Backwell et al., 1998). Observations from various studies aligns with these concepts. For instance, Choi et al. (2016), found that shorebirds in a crucial wintering site along the East Asian- Australasian Flyway preferentially consumed smaller, more abundant and accessible prey over larger potentially profitable prey. Additionally, at sites with lower prey densities, the efforts associated with capturing prey was much higher (Jackson et al., 2024), The extent of interspecific competition or coexistence among shorebird species is largely determined by food availability or the capacity for niche segregation (Choi et al., 2016). Given the ongoing degradation of critical shorebird habitats, investigating their feeding ecology of shorebirds is essential for assessing the broader ecological consequences of habitat loss.

There exists a broad correlation between shorebird morphology and foraging ecology, underscoring the role of co-evolution in the survival of these threatened species (Barbosa & Moreno, 1999; Yu et al., 2023). Morphological traits, such as the length of the tarsometatarsus and bill, play crucial roles in shaping the foraging strategies and dietary niches of shorebirds (Thomas et al., 2006; Dias et al., 2009; Lourenço et al., 2016). A study in the Americas by Hall et al. (2021), reported the preference of smaller prey items by juvenile shorebirds, suggesting the influence of morphology on prey selection. Therefore, morphological diversity among species facilitates resource partitioning, thereby reducing direct competition and supporting species coexistence within the habitats (Bocher et al., 2014; Duijns et al., 2014; Forsman & Wennersten, 2016). However, this adaptability is being increasingly challenged by significant habitat degradation, particularly at critical stopovers and wintering grounds (Wang et al., 2022; Shamna et al., 2023; Studds et al., 2017).

Despite extensive studies on shorebird foraging ecology, most studies have focused on species along the American Flyways (Faria et al., 2018; Martinez-Curci et al., 2015; Novcic, 2019), the African-Eurasian Flyway (Bocher et al., 2014; Lourenço et al., 2016, 2017) and the East Asian-Australasian Flyway (Huang et al., 2022). In contrast, the dietary niche dynamics of shorebirds along the Central Asian Flyway remain poorly understood. Given the ecological significance of this flyway, where several species undertake long-distance migrations, investigating their diet composition is crucial. Additionally, the diet spectrum and foraging behaviours of shorebird species, could vary with geographical locations (Masero et al., 2007). Investigating regional patterns of prey selection is essential for the conservation and protection of shorebirds and their critical wintering sites. This is the first comprehensive research to examine the diet spectrum of shorebirds in key wintering sites within the CAF, contributing to the broader understanding of their foraging ecology.

India serves as a critical wintering ground for shorebirds along the CAF. During this season, migratory shorebirds are prominently found along India's west coast, particularly within the KVCRR, which features intertidal mudflats, mangroves, and sandy beaches (Rashiba et al., 2022; Rao et al., 2022). Research highlights the importance of intertidal ecosystems as crucial habitats for shorebirds, providing diverse feeding opportunities (Mathot et al., 2018). In KVCRR, the bare mudflats exposed during low tide support a rich diversity and abundance of polychaete worms, followed by crustaceans, whereas mangroves, characterized by vegetated mud habitats, exhibit a higher diversity and abundance of crustaceans compared to polychaetes (Aarif, 2009). Adjacent sand beaches near KVCRR, featuring predominantly *Cosmonotus* Crab (*Emerita holthuisi*), serve as alternative foraging areas during high tide (Aarif, 2009; Aarif et al., 2014). However, over the past two decades, KVCRR has witnessed a significant decline in prey diversity and abundance, attributed to increased relative humidity, air and water temperatures, and salinity levels (Aarif et al., 2021a). This decline has profoundly impacted shorebird populations, contributing to their drastic decrease in numbers.

Shorebird species such as, Eurasian Curlew (*Numenius arquata*) and Bar-tailed Godwit (*Limosa lapponica*) are currently designated as near threatened (NT) by the IUCN (Pearce-Higgins et al., 2017; Viana et al., 2023). They belong to the tribe Numeniini, which has experienced alarming population declines across multiple flyways including CAF (Pearce-Higgins et al., 2017; Cook et al., 2021; Aarif et al., 2021a). While few studies from other regions have explored their diet spectra (Scheiffarth, 2001; Li et al., 2020; Navedo et al., 2020), comprehensive studies from the CAF remain lacking.

The Bar-tailed Godwits exhibit specialized foraging behaviours and prey preferences to avoid conspecific competition during the non-breeding period (Duijns & Piersma, 2014). Their larger size enables them to spend less time foraging by targeting larger and more profitable prey (Choi et al., 2016). They predominantly employ tactile foraging techniques, using their elongated, straight beaks, equipped with sensory pits (Davidson et al., 1986; Quindlen-Hotekand et al., 2020). However, they can to some extent switch from one to other foraging modes in response to environmental conditions and prey availability (Dias et al., 2009). The composition and abundance of prey items for Bar-tailed Godwit vary across habitat types, influencing their distribution across geographic and microgeographic region, which in turn, has significant implications for their population dynamics (Angarita-Báez & Carlos, 2023a). Enhancing knowledge of the diets and understanding how alterations in habitat conditions influence their diet and foraging behaviour is essential for developing targeted conservation strategies to mitigate prey depletion and habitat degradation (Hacker et al., 2021).

Results

Multi-habitat assessment of prey capture rates of Eurasian Curlew and Bar-tailed Godwit

As capture rate data and total prey capture were not normally distributed, a log transformation was applied, followed by the addition of 2 to address missing values (NAs) in R. The resulting model residuals adhered to a normal distribution, and all predictors exhibited VIF values below 2.0, indicating low multicollinearity.

Subsequently, a model explaining Capture Rate (CRlog) was selected using Time duration (TD), microhabitat, species, year, and foraging depth. This model was chosen due to its lowest AIC value (-17288). Residuals were symmetrically distributed around zero, suggesting a small variance and a good model fit. Variables such as sex and month did not significantly impact the capture rate and were excluded (Table 5). The negative and significant coefficient for Time Duration (-0.0814) indicated that the capture rate decreased with each unit increase in TD (Table 5).

Compared to mangroves, mudflats, and sandy beaches have coefficients of -0.086 and -0.017, respectively. Both coefficients are significantly different from zero, indicating that these microhabitats are associated with lower capture rates than mangroves (Table 5).

The utilization of different habitats varied between the two species. The Eurasian Curlew is more adaptable, thriving in diverse environments, especially marshes and sandy beaches. Even so, Eurasian Curlews exhibited significantly lower capture rates (Figure 7) compared to Bar-tailed Godwits, as indicated by a negative and significant coefficient ($p < 0.001$) (Table 5). Both medium success and superficial success have positive coefficients and statistically significant p-values, indicating that the capture rate is higher in these foraging depths compared to deep foraging.

The trend shows that the capture rate decreased between 2010 and 2019 for both species; however, a slightly increasing trend was observed in 2020 for both species, for Bar-tailed Godwit showed 2021 also slightly increasing trends of Capture rate (Figure 8).

The Bar-tailed Godwit exhibits a stronger preference for mudflats (Figure 9), despite having a higher capture rate in mangroves. This specialization suggests that the Bar-tailed Godwit may be adapted to capture specific prey abundant in these ecosystems. In Eurasian Curlew, feeding abundance trends over the years and across habitats indicate that sand beaches had the highest abundance, followed by mangroves, with the lowest observed on mudflats (Figure 10).

Table 5. Results of a generalized linear model (GLM) examining the effects of time duration, microhabitat, sex, species, and deep success on total prey capture by Bar-tailed Godwits and Eurasian Curlew in the western coast of India (2012-2021).

Coefficients:	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	1.194	0.006	198.073	<0.001
Time duration	-0.081	0.000	-86.197	<0.001
Mudflats	-0.086	0.005	-16.235	<0.001
Sand beach	-0.017	0.004	-4.199	<0.001
Eurasian Curlew	-0.014	0.004	-3.144	0.001
Medium Success	0.039	0.001	35.127	<0.001
Superficial Success	0.055	0.001	55.44	<0.001

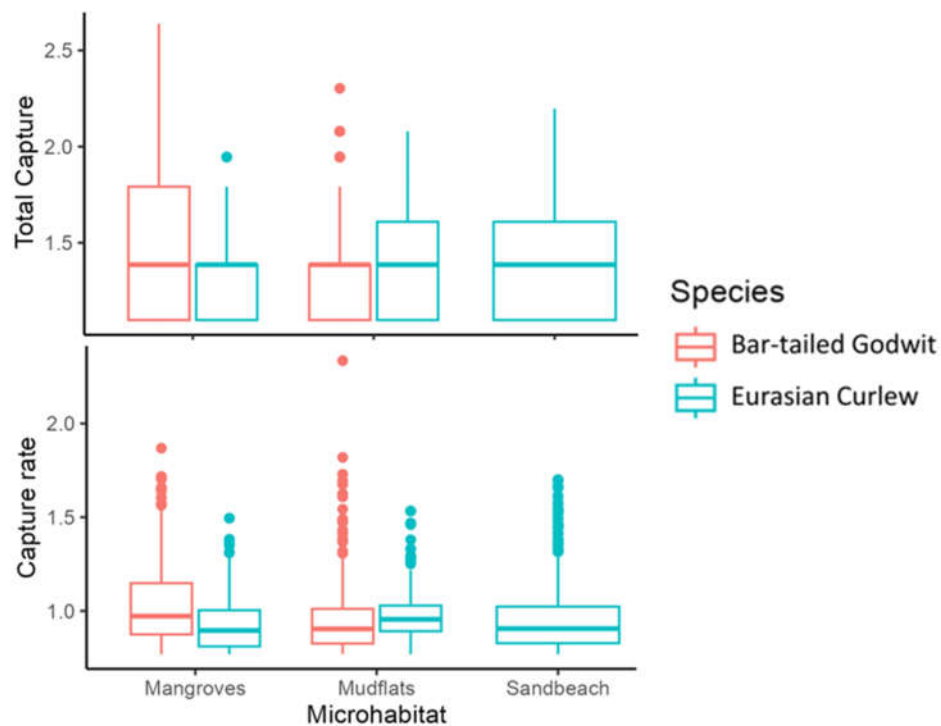


Figure 7: Box plot comparing capture rates and total prey captured between Bar-tailed Godwit (*Limosa lapponica*) and Eurasian Curlew (*Numenius arquata*) in three different microhabitats (mangroves, mudflats, and sand beaches) between 2010-2021 along the west coast of India.

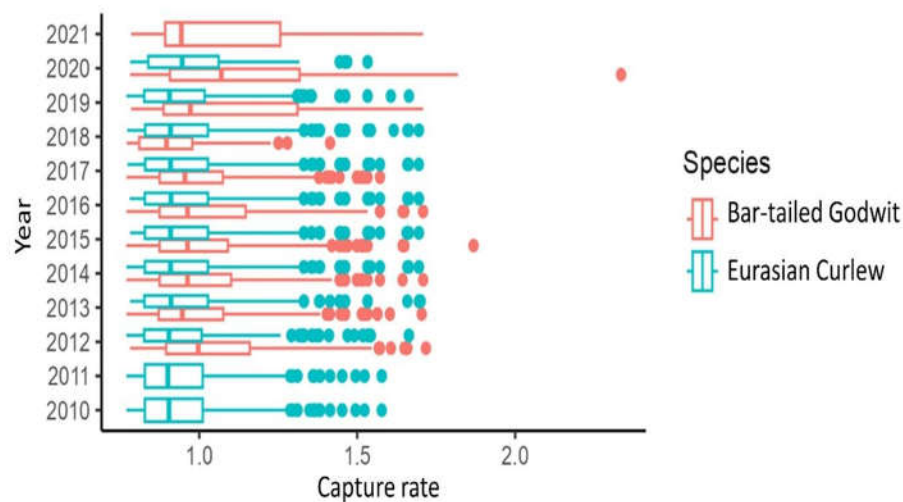


Figure 8. Box plot comparing total captured rate between Bar-tailed Godwit (*Limosa lapponica*) and Eurasian Curlew (*Numenius arquata*) between 2010-2021 along the west coast of India.

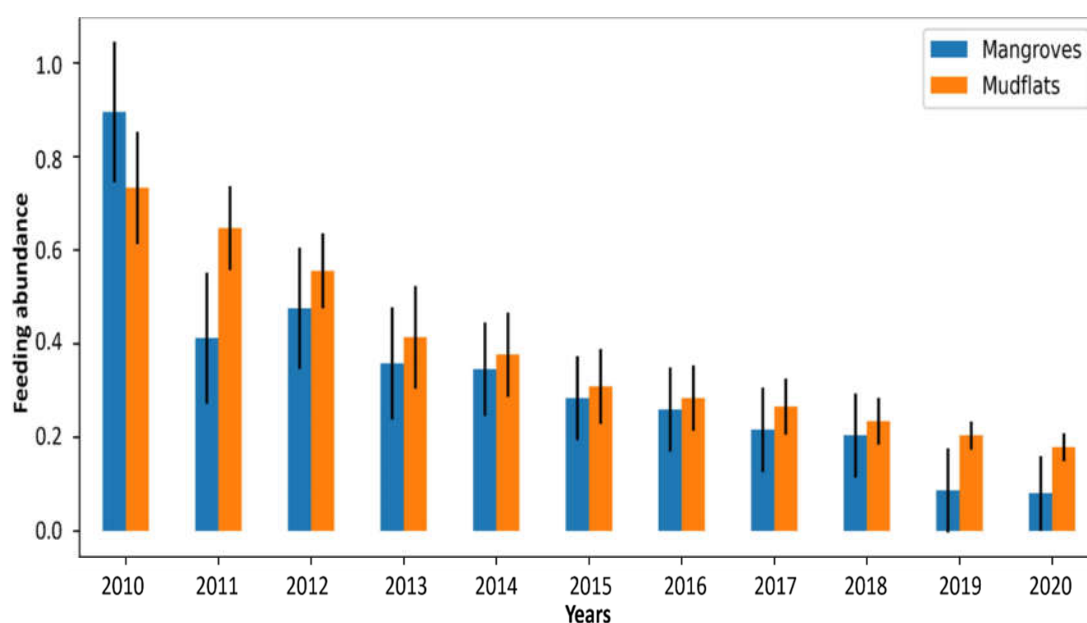


Figure 9. Abundance of actively foraging Bar-tailed Godwit (*Limosa lapponica*) between 2010 and 2020 in three habitats on the west coast of India: KVCR mudflats and KVCR mangroves.

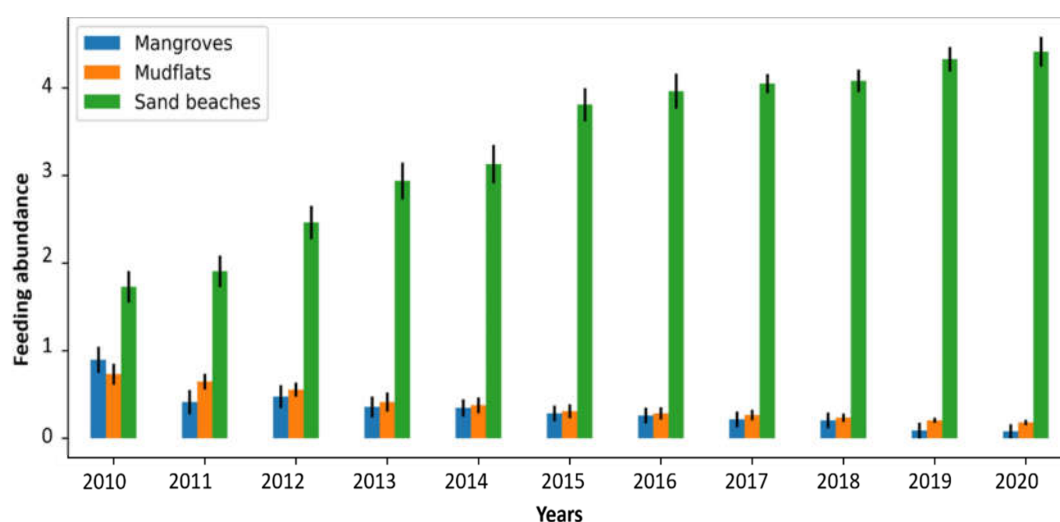


Figure 10. Abundance of actively foraging Eurasian Curlew (*Numenius arquata*) between 2010 and 2020 in three habitats on the west coast of India: KVCR mudflats, KVCR mangroves, and adjoining sand beaches.

Uncommon foraging strategies of Bar-tailed Godwit in sand beaches

The Bar tailed Godwit capture success varies significantly over years, months, sites and foraging techniques (Table 6 & 7). The GLM analysis showed that these four variables together had the strongest influence on capture success (Table 8).

Table 6. Table summarizing average values of capture success over years, months, sites and foraging techniques

Variables	Categories	Mean	SE
Year	2016	0.350	0.013
	2017	0.302	0.010
	2018	0.327	0.017
	2019	0.318	0.024
	2020	0.509	0.041
	2021	0.275	0.023
	2022	0.619	0.070
Month	January	0.339	0.022
	February	0.383	0.020
	March	0.270	0.013
	October	0.412	0.027
	November	0.325	0.012
	December	0.339	0.016
Site	Ariyallur	0.335	0.013
	Kappad	0.323	0.012
	Pulimoodu	0.349	0.013
Foraging technique	Zigzag	0.351	0.009
	Straight-line	0.310	0.012

Table 7. Variables significance on capture success (response variables) based on the top models for the Bar- tailed Godwit over explanatory variables.

Effect ($R^2=0.30$)		df	F	P
Intercept	Fixed	1	993.7168	0.000000
Year	Fixed	6	13.7637	0.000000
Month	Random	5	3.5226	0.003893
Site	Random	2	3.5481	0.029562
Foraging technique	Fixed	1	6.9391	0.008714
Error		465		

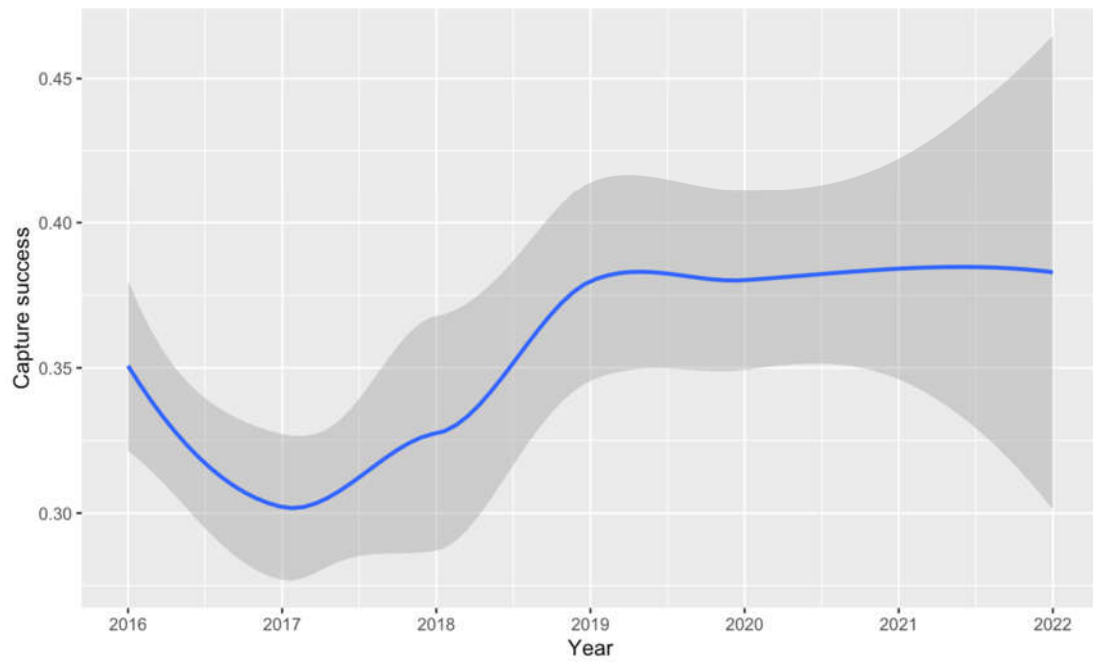
Table 8. Generalized Linear Model showing a summary of models for measures of capture success (response variable) over environmental explanatory variables.

Explanatory variables	K	AIC	Delta AIC	AIC Wi
Year, Month, Site, Foraging technique	5	-436.136815	0.000000	0.84792686
Year, Month, Site	4	-431.649232	4.487583	0.08992743
Year, Month, Foraging technique	4	-430.482256	5.654559	0.05017491
Year, Site, Foraging technique	4	-427.616172	8.520643	0.01197083

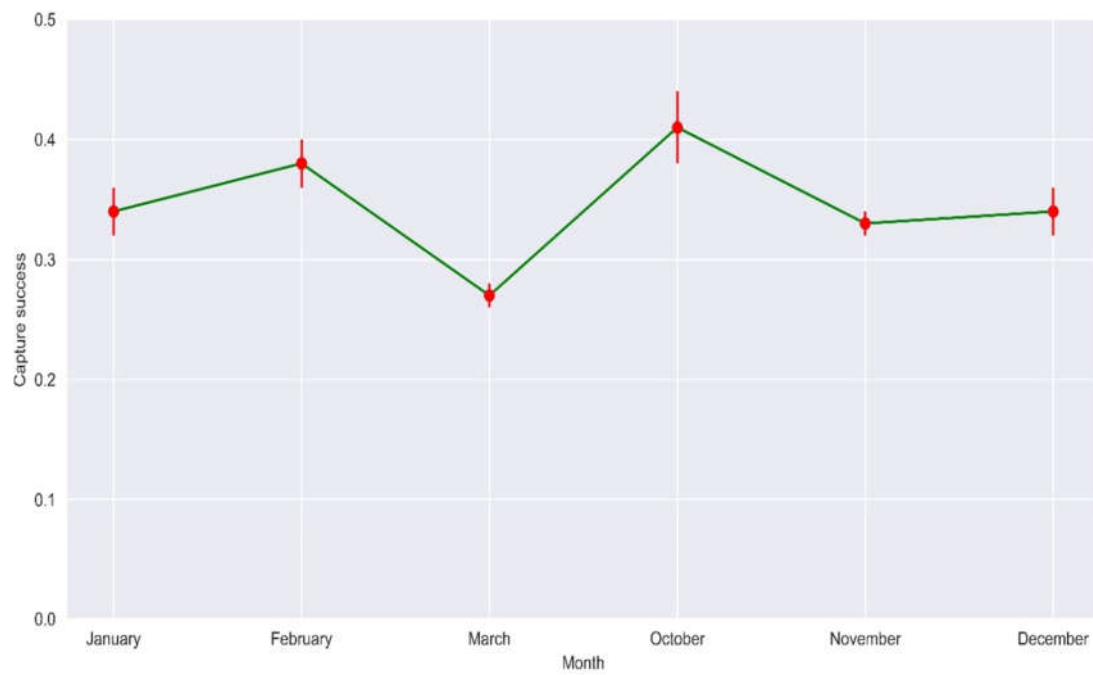
The capture success fluctuates over the years, being significantly highest ($F = 13.76$; $df = 6$; $P < 0.001$) in 2022 with 0.61 ± 0.07 captured prey per all attempts (Figure 11a).

The highest capture success rate ($F = 3.52$; $df = 5$; $P < 0.01$) is recorded in February (0.38 ± 0.02) and October (0.41 ± 0.02) and the lowest in March (0.27 ± 0.01) (Figure 11b). The Bar-tailed Godwit shows highest and lowest ($F = 3.54$; $df = 2$; $P < 0.05$) capture success rates in Pulimoodu (0.35 ± 0.01) and Kappad (0.32 ± 0.01) sites respectively (Figure 11c). Capture success was highly linked to the adopted foraging technique ($F = 6.93$; $df = 1$; $P < 0.001$), being highest when Bar-tailed Godwit uses the zigzag mode (0.35 ± 0.009) and lowest with straight-line mode (0.31 ± 0.01) (Figure 11d).

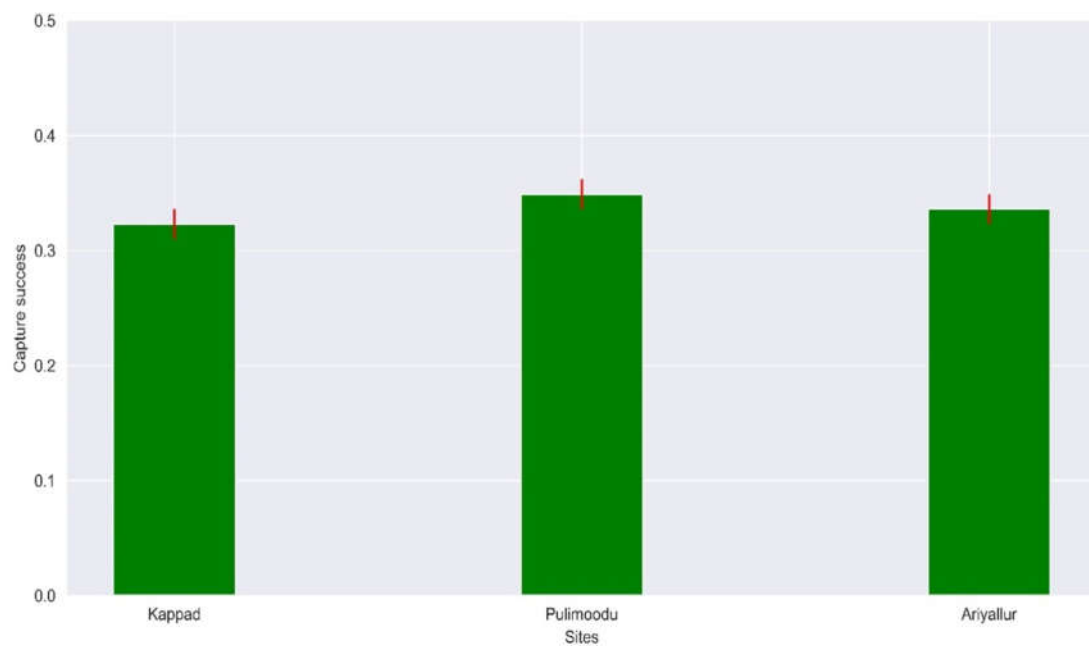
a)



b)



c)



d)



Figure 11: Mean of consumed prey recorded by the Bar tailed Godwit according to years; (a) years, (b) months, (c) sites and (d) foraging techniques (Vertical bars denote +/- standard errors).

Additionally, there is a significant variation in the distribution of prey categories consumed by the Bar-tailed Godwit depending on the foraging technique employed ($\chi^2 = 49.25$; $df = 4$; $P < 0.001$). Notably, *Cosmonotus* crab (*Emerita holthuisi*) constitutes the most consumed prey, whether through zigzag (76.12%) or straight-line (72.06%) mode of foraging behaviours (Table 9; Figure 12). The second most

important prey consumed was small crabs, followed by bivalves. Prey with lower capture rates includes prawns, accounting for only 1.14% of the overall prey consumed.

Bar-tailed Godwit consumes the majority of *Cosmonotus* crabs (66.67%), other crabs (61.54%), and all recorded bivalves (100%) using the zigzag mode of foraging. Meanwhile, the straight-line foraging mode (Table 9) is used to consume all prawns and 89.47% of aquatic insects (Table 9).

Table 9. Distribution of prey capture proportions according used foraging mode. (N: Number of prey consumed, %: percentage)

Prey category	Prey consumed using Zigzag			Prey consumed using Straight-line			Overall prey captured	
	N	% (between prey)	% (between behaviour)	N	% (between prey)	% (between behaviour)	N	% (between prey)
Cosmonotus crabs	392	76.12	66.67	196	72.06	33.33	588	74.71
Crabs	80	15.53	61.54	50	18.38	38.46	130	16.52
Bivalves	41	7.96	100.00	0	0.00	0.00	41	5.21
Prawns	0	0.00	0.00	9	3.31	100.00	9	1.14
Aquatic insects	2	0.39	10.53	17	6.25	89.47	19	2.41
TOTAL	515	100.00		272	100.00		787	100.00

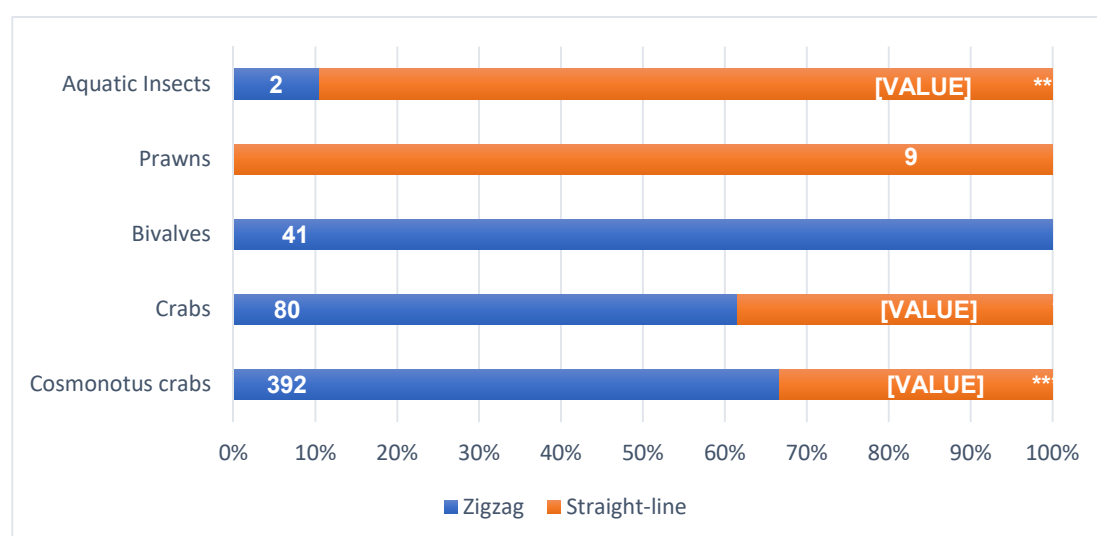


Figure 12. Variation of prey capture proportions between the two-foraging mode (* is the significance probability of the relationship).

Diet spectrum of Eurasian Curlew and Bar-tailed Godwit

Data collection for this study spanned from 2010 to 2022, with observation durations varying for each species. Bar-tailed Godwits were observed for six months annually between 2012 and 2017, with reduced observation periods in subsequent years (five months in 2018, one month in 2019, and two months in both 2020 and 2022). Conversely, Eurasian Curlews received the most extensive data collection, with observations conducted for eight months annually from 2010 to 2020. Bar-tailed Godwits were observed as foraging the most during February and March, while Eurasian Curlew during February, March, and April.

A total of 2,185 Bar-tailed Godwit and 8,592 Eurasian Curlew individuals were observed. Throughout the observation period, 39,845 min of video footage was recorded. This subset was further divided as follows: Bar-tailed Godwit (8,122 min), and Eurasian Curlew (31,723 min). Bar-tailed Godwit spent more than 60% of its foraging time in mangroves, compared to mudflats. Notably, data from beaches were excluded due to the Bar-tailed Godwit employing unique foraging strategies in that environment, differing significantly from their behaviour in mangroves and mudflats. On the other hand, Eurasian Curlew was observed foraging for over 85% of the time on sand beaches, and less time spent in mangroves and mudflats. Sandy beaches were thus identified as the most frequented habitat for this species.

The Bar-tailed Godwit primarily fed on small crabs and polychaetes, which accounted for over 70% of its prey items. Other prey items included shrimps and soft bivalves. The Eurasian Curlew's diet consisted mainly of small fishes and mole crabs, together comprising more than 50% of its diet. Large and medium crabs, aquatic insects, and shrimp were also consumed (Table 10).

In mangroves, the most captured prey for Bar-tailed Godwits were polychaetes, while aquatic insects for Eurasian Curlews. In mudflats, small crabs were the prey most frequently captured by Bar-tailed Godwits, and Eurasian Curlews primarily captured small fishes (Table 10).

Table 10. Frequency of occurrence (FO%) is given as a percentage for each of the prey items recorded for each shorebird. N = number of records made by video recorder (v) and droppings (d). Data collected between 2010 and 2020 on the west coast of India.

Shorebird Habitat	Bar-tailed Godwit					Eurasian Curlew					
	Mangroves	Mudflats	Beach	Mangroves	Mudflats	Beach	Mangroves	Mudflats	Beach	Mangroves	Mudflats
Number	1425 (v)	32 (d)	264 (v)	36 (d)	43(d)	725	36(d)	353(v)	41(d)	6198(v)	43(d)
Polychaetes	72.1	53.1	45.1	50.0	0.0	0.0	8.3	0.0	9.8	0.0	0.0
Small Crabs	<u>68.4</u>	<u>65.6</u>	<u>79.5</u>	<u>72.2</u>	0.0	0.0	<u>100.0</u>	0.0	<u>97.6</u>	0.0	0.0
Medium Crabs	0.0	50.0	0.0	66.7	<u>62.8</u>	27.9	22.2	37.1	19.5	17.1	32.6
Shrimps	25.4	31.3	5.3	61.1	39.5	1.4	25.0	0.0	46.3	14.9	30.2
Aquatic Insects	0.0	0.0	0.0	25.0	23.3	<u>54.9</u>	25.0	51.8	14.6	11.0	14.0
Cosmonotous crabs	0.0	25.0	0.0	0.0	55.8	0.0	0.0	0.0	0.0	33.6	<u>90.7</u>
Soft Bivalves	13.4	21.9	6.1	25.0	18.6	0.0	27.8	0.0	39.0	0.0	20.9
Large Crabs	0.0	0.0	0.0	0.0	0.0	6.1	0.0	7.4	0.0	3.4	0.0
Small Fishes	0.0	0.0	0.0	0.0	0.0	45.5	0.0	<u>54.1</u>	0.0	<u>53.3</u>	0.0

To examine dietary overlap between the two species, Non-metric Multidimensional Scaling (NMDS) was used. This technique allows us to visualize the degree of similarity between samples based on their species composition. A low stress value of 0.12 indicates that the two-dimensional NMDS plot provides a reasonable representation of the original multidimensional data.

The diets of the shorebirds share several prey items, with only Large Crabs and Small Fishes being exclusively consumed by Eurasian Curlews. To quantify the dietary similarity, the Bray-Curtis similarity index was calculated. Despite variations in the number of individuals collected among each species, the low index value of 8% suggests a limited dietary overlap between the two species. This low overlap can be explained by differences in prey selection, such as Bar-tailed Godwits consuming polychaetes and small-sized crabs more frequently, while Eurasian Curlews primarily favor fishes and aquatic insects (Figure 13 and Table 10).

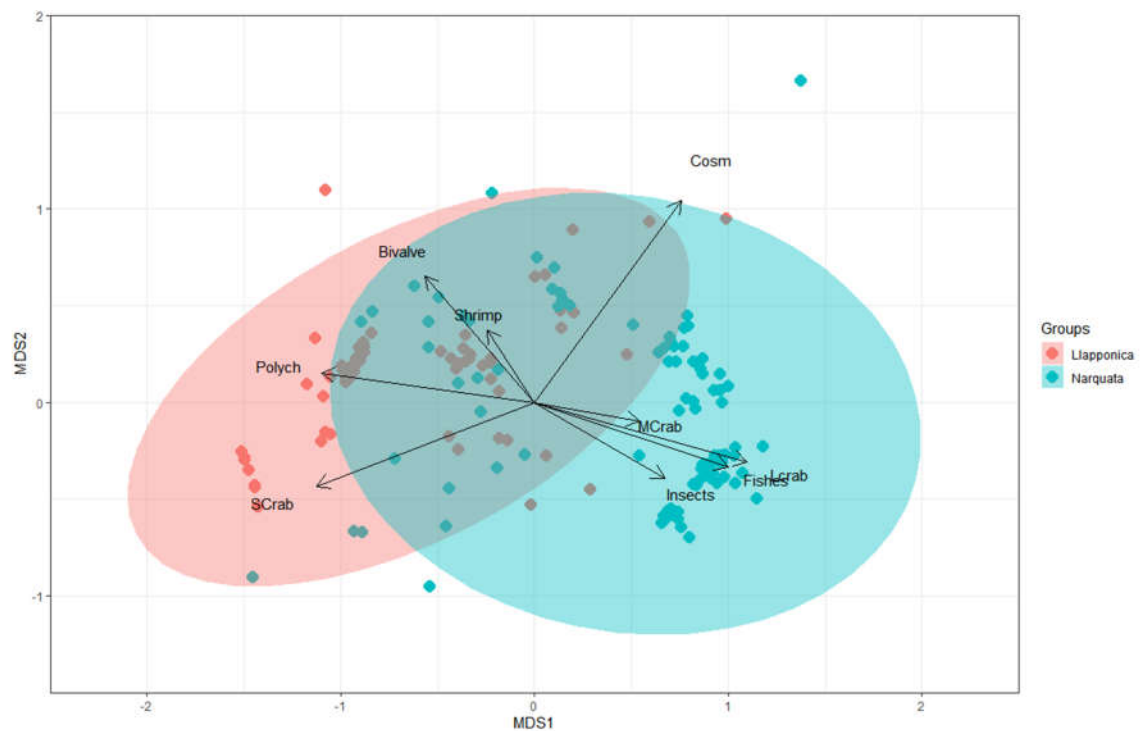


Figure 13. Results of nMDS analysis to identify dietary similarity between shorebirds on the west coast of India. The red ellipse corresponds to Bar-tailed Godwits, and the blue ellipse corresponds to Eurasian Curlews.

The Bray-Curtis index, which yielded an intermediate value (43%) for mudflats and mangroves, indicate a similar composition in their communities. In contrast, the index produced lower values when comparing these habitats to sand beaches (19%), suggesting a more distinct community composition in sand beaches. Although differences in the amount of prey consumed were found, only a slight variation in consumption of small-sized crabs was observed, with higher consumption in mudflats. Mole crabs were found to be more frequently consumed on the sand beaches (Figure 14).

A total of 231 droppings were collected, of which 111 droppings from Bar-tailed Godwit and remaining 120 droppings from Eurasian Curlew at mudflats, mangroves and sand beaches. Through droppings, seven types of prey consumed by the shorebirds were identified: polychaetes, small crabs, medium crabs, shrimp, aquatic insects, Cosmonotus crabs, and soft bivalves. Analysing the number of shorebirds for which it was possible to identify the captured prey, it was found that in

mangroves and mudflats, small crabs appear most frequently as the primary prey for both Bar-tailed Godwits and Eurasian Curlews. In sandy beaches, *Cosmonotus* crab is the dominant prey for both species of shorebirds. Overall, small crabs in mangroves & mudflats and *Cosmonotus* crabs in sand beaches are the most significant items in the shorebirds' diet (Table 10).

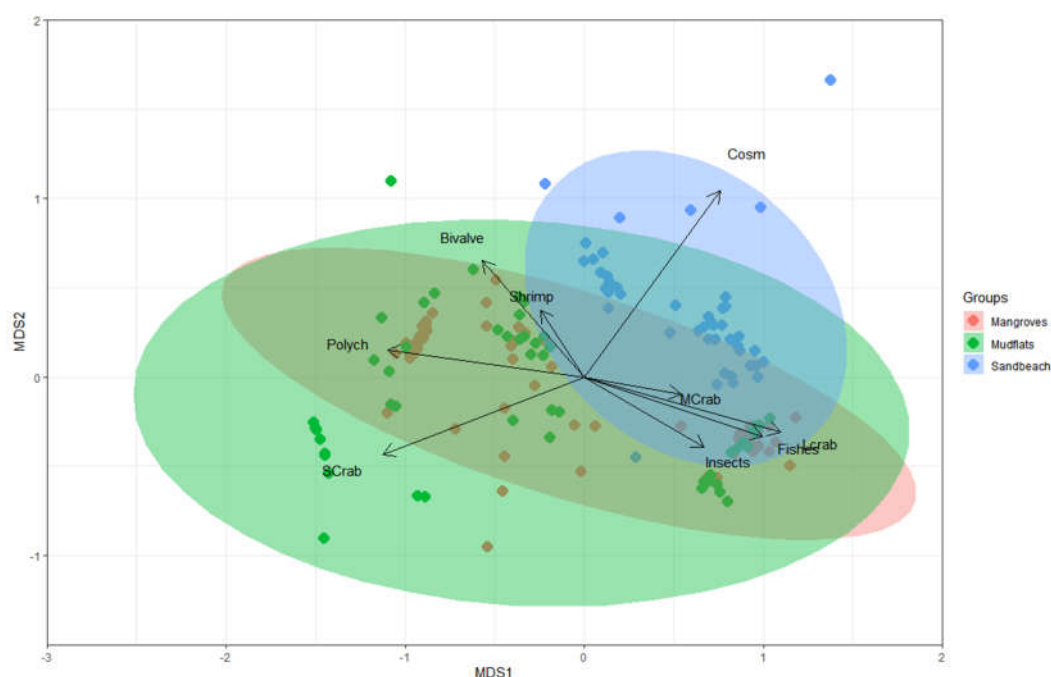


Figure 14. Results of nMDS analysis to identify dietary similarity between shorebirds in three habitats on the west coast of India. The red ellipse corresponds to mangroves, the big green ellipse represents mudflats, and the little blue ellipse corresponds to sand beach.

The Chi-squared test revealed significant association between certain prey types and habitats ($p < 0.001$). Polychaetes, small crabs and *Cosmonotus* crabs showed statistically significant preferences for specific habitats, whereas other prey types did not exhibit any significant association. Among them, polychaetes and small crabs were predominantly associated with mudflats and mangroves, while *Cosmonotus* crab was primarily associated with sand beaches (Table 11). Additionally, the Chi-squared test indicated a significant association between species and certain prey types ($p < 0.001$). Polychaetes and medium crabs exhibited a highly significant association with Bar-tailed Godwit compared to Eurasian Curlew (Table 11).

Table 11. Estimated Marginal Means (EMMs) and Standard Errors (SE) for different prey types across habitats (mudflats, mangroves, sand beaches) and species (Bar-tailed Godwit, Eurasian Curlew). EMMs represent the average association of each prey type with habitats and species. Significant pairwise comparisons between habitats and species are included. Mangroves and mudflats have significantly higher association with polychaetes and small crabs, compared to sand beaches ($p < 0.001$). Bar-tailed Godwits have a significantly higher association with polychaetes and medium crab relative to Eurasian Curlews ($p < 0.001$).

	Prey types	Groups	EMMs	SE	Contrast	Estimate	SE	t-ratio	p value
Habitats	Polychaetes	Mangroves	1.294	0.0439	Mudflats - Mangroves	0.0084	0.0602	0.140	1.00
		Mudflats	1.286	0.0412	Mangroves - Sand beaches	0.2941	0.0587	5.011	<0.001
		Sand beaches	0.00	0.0390	Mudflats - Sand beaches	0.2857	0.0568	5.035	<0.001
	Small crabs	Mangroves	0.10	0.0651	Mudflats - Mangroves	-0.0399	0.0893	-0.447	1.00
		Mudflats	0.14	0.0612	Mangroves - Sand beaches	1.1029	0.0871	12.661	<0.001
		Sand beaches	0.00	0.0579	Mudflats - Sand beaches	1.1429	0.0842	13.569	<0.001
	Cosmonotus crabs	Mangroves	0.00	0.6837	Mudflats - Mangroves	0.00	0.0874	0.00	1.00
		Mudflats	0.00	0.0599	Mangroves - Sand beaches	-1.03	0.0852	-12.142	<0.001
		Sand beaches	1.03	0.0566	Mudflats - Sand beaches	-1.03	0.0824	-12.559	<0.001
Species	Polychaetes	Bar-tailed Godwit	0.3153	0.0347	Bar-tailed Godwit - Eurasian Curlew	0.257	0.0481	5.342	<0.001
		Eurasian Curlew	0.0583	0.0333					
	Medium crabs	Bar-tailed Godwit	0.676	0.0497	Bar-tailed Godwit - Eurasian Curlew	0.426	0.069	6.171	<0.001
		Eurasian Curlew	0.250	0.0478					

Significance levels denoted by $p < 0.001$ are indicated in bold. Pairwise comparisons were adjusted using the Bonferroni correction for multiple testing, with a 95% confidence level.

Population dynamics of Eurasian Curlew and Bar-tailed Godwit

The overall population dynamics have shown declining trends over the years (Figure 15). The abundance was its highest in 2010, while the lowest abundance was recorded in 2023, showing a statistically significant temporal variation (ANOVA: $F_{(13,70)} = 53.6, p < 0.001$). Additionally, the abundance trends of both species were declining across all habitats (ANOVA: $F_{(2,81)} = 25.6, p < 0.001$; Figures 16 & 17). The abundance of both species at sand beaches was significantly higher than both mudflats and mangroves. There is no significant difference was found between mudflats and mangroves (Figure 18).

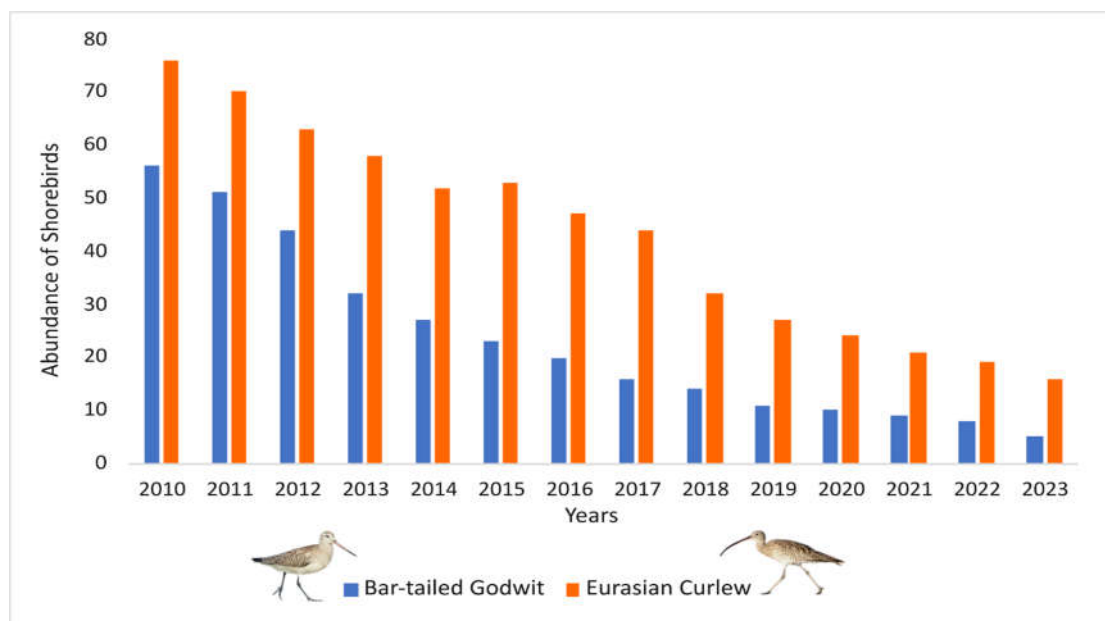


Figure 15. Declining abundance trends of Bar-tailed Godwit and Eurasian Curlew between 2010 to 2023.

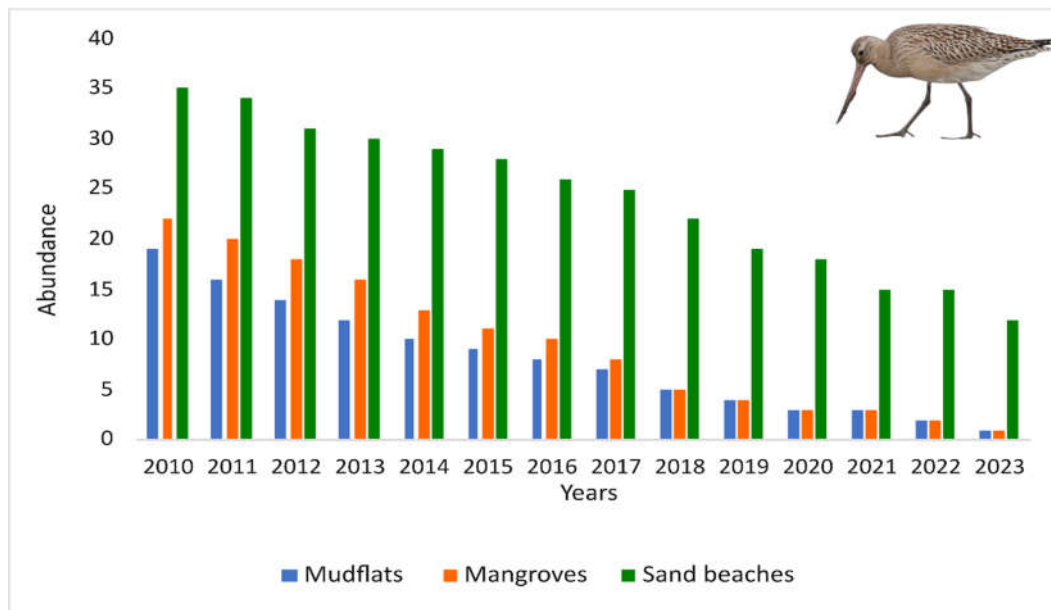


Figure 16. Population dynamics of Bar-tailed Godwit (*Limosa lapponica*) at mudflats, mangroves and sand beaches between 2010 to 2023, 14 years of study.

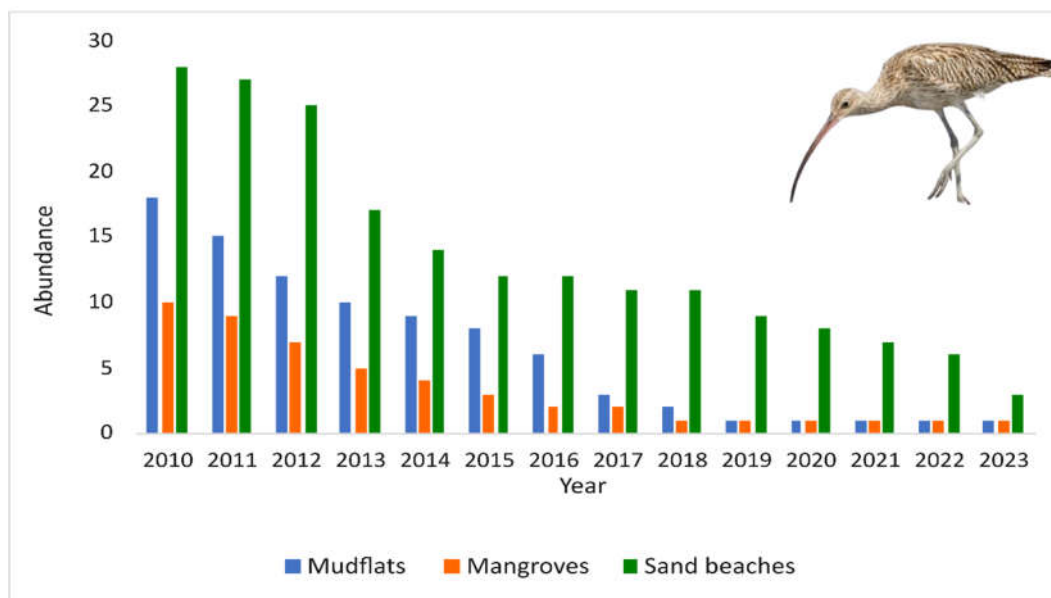


Figure 17. Population dynamics of Eurasian Curlew (*Numenius arquata*) at mudflats, mangroves and sand beaches between 2010 to 2023, 14 years of study.

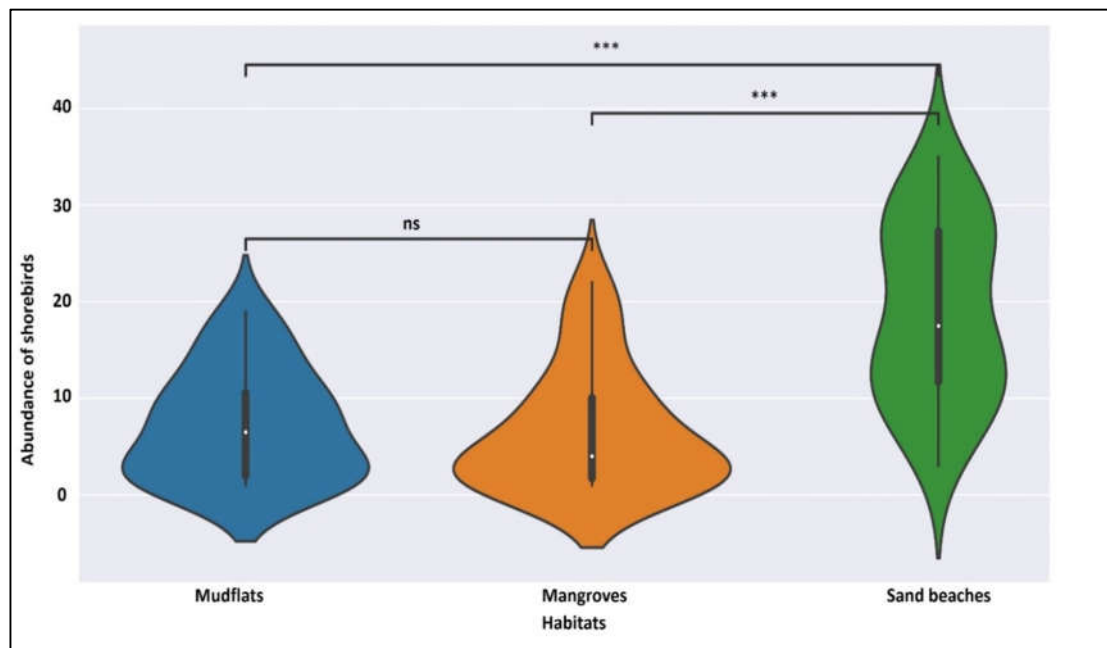


Figure 18. Distribution of shorebird abundance (Eurasian Curlew and Bar-tailed Godwit) across mudflats, mangroves and sand beach habitats. Tukey's HSD post hoc analysis revealed that sand beaches significantly differed from mudflats and mangroves ($***p < 0.001$), while no significant variation was observed between mudflats and mangroves (ns: non-significant).

Discussion

Multi-habitat assessment of capture rates of Eurasian Curlew and Bar-tailed Godwit

The study revealed that capture rates of both Eurasian Curlew and Bar-tailed Godwit were the lowest at mudflats and sand beaches compared to mangroves. This highlights the complexity of foraging habitat selection and its implications for conservation (Jing et al., 2006; Mu and Wilcove, 2020). Both are versatile foragers primarily employing tactile foraging, yet they can switch to visual foraging when advantageous (Finn et al., 2007). Tactile foraging depends on mechanoreceptors located in the bill that detect prey through pressure and vibrations (van de Kam et al., 2004).

Several factors can influence the foraging efficiency of shorebirds, including their morphology, prey density, substrate properties, microhabitat conditions, and human disturbances (Angarita-Báez & Carlos, 2023a; Jackson et al., 2024). At KVCR,

Rubeena et al. (2023) documented significant alterations in substrate quality, which likely hindered tactile foraging (Yu et al., 2023). Prey accessibility for probing shorebirds is highly dependent on substrate penetrability and prey behaviour, with prey proximity to the surface fluctuating with environmental conditions (Fujii, 2012).

Structural modifications in the feeding grounds, such as the recent sand deposition reported in the KVCR mudflats, have altered the sediment texture, making it less suitable for probing (Aarif & Musammilu, 2018; Rubeena et al., 2023). Sand beaches and sand-deposited mudflats consist of coarser grains, which release heat more rapidly than muddier sediments that retain moisture (Zhu et al., 2022). The increased dryness of these sandy substrates limits bill probing movements, contributing to reduced capture rates (Myers et al., 1980; Milsom et al., 2002). As a result, shorebirds may experience greater capture success in wet, penetrable sediments, such as those found in mangroves, where capture rates are higher. Additionally, the present study observed that shorebirds achieved greater capture rates at superficial and medium foraging depths compared to deep probing modes. Deep probing is generally associated with slow, time-consuming efforts to capture deeply buried larger prey (Baguette et al., 2023). Moreover, this study revealed that foraging time duration is higher at mudflats and sand beaches compared to mangroves. This further highlights the diminished prey availability in these habitats, as longer foraging durations are associated with reduced capture rates (Thaxter et al., 2013). Shorebirds may adapt by switching to pecking strategies in drier sediments. However, this strategy remains constrained in KVCR mudflats due to the rising air and water temperatures, which cause prey to burrow deeper and become inaccessible (Aarif et al., 2021a). Therefore, sediment hardening and concurrent shifts in prey behaviour likely represent key drivers behind the declining capture rates observed in KVCR mudflats compared to mangroves.

Shorebird distribution is shaped not only by physical environmental factors but also by species-specific feeding adaptations to these variables (Isacch et al., 2005). The

study further identified that Bar-tailed Godwits achieved their prey capture rates in mangroves, whereas Eurasian Curlews were in mudflats and sand beaches. This variation may be attributable to differences in morphological traits and foraging strategies, as well as the changing microhabitat conditions. The Eurasian Curlew's long, curved beak is adapted for slow probing into the substrate, while the Bar-tailed Godwit employs rapid probing with its straight beak (Davidson et al., 1986). The probing behaviour of Bar-tailed Godwits may affect their sensory receptors more than the slower-probing Eurasian Curlews (Davidson et al., 1986). This may potentially lead to a preference for wet and soft substrates like those found in mangroves under conditions of sediment hardening in mudflats. Additionally, Bar-tailed Godwits were observed washing their prey in the water column before swallowing, which necessitates a water column near their foraging grounds, which is readily met in mangrove fringes compared to dry mudflats. It was observed that Eurasian Curlews had significantly lower capture rates compared to Bar-tailed Godwits. The finding also underscores the efficient visual foraging ability of Bar-tailed Godwits compared to Eurasian Curlew, warranting further investigation.

The annual trend of capture rates indicates a decrease between 2010 and 2019 for both species, which may be linked to habitat changes and declining prey availability over the years (Aarif et al., 2011, 2021). However, a slight increasing trend was observed in 2020 for both species, with Bar-tailed Godwit showing a further slight increase in 2021. This fluctuation may be associated with reduced human activity during the COVID-19 pandemic and lockdowns. Lewis et al. (2022) similarly documented an inverse relationship between shorebird activity and human presence during the pandemic period. Additionally, Botto et al. (2008) reported that even low levels of human presence, while not causing flushing of shorebirds, significantly reduced their foraging efficiency. Further studies could benefit from exploring how changes in prey behaviour and availability interact with human disturbances to affect shorebird foraging success.

Consistent with capture rate trends, the feeding abundance trends indicate that sand beaches had the highest abundance for Eurasian Curlews, followed by mangroves, with the lowest observed on mudflats. Conversely, for Bar-tailed Godwit, the greatest abundance was found in mudflats (Figure 19). This highlights the direct impact of habitats on their feeding abundance. Bar-tailed Godwits were observed switching their foraging behaviour while Eurasian Curlew altered their habitat preferences to adapt to changing conditions along the wintering grounds on the west coast of India.

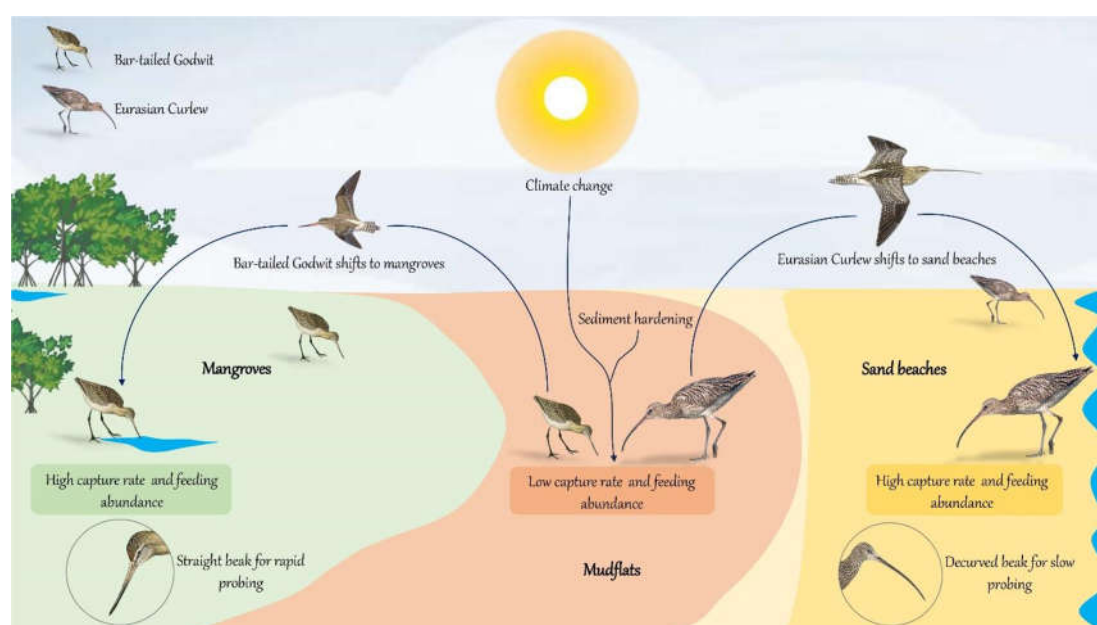


Figure 19. Depicting the habitat switching patterns of Eurasian Curlew and Bar-tailed Godwit of KVC mudflats in response to sediment hardening and environmental changes. Eurasian Curlew shifts to sand beaches, while Bar-tailed Godwit transitions to mangroves, optimizing foraging efficiency due to reduced prey availability.

Uncommon foraging strategies of Bar-tailed Godwit at sand beaches

The study revealed an uncommon foraging strategy observed among Bar-tailed Godwits within sand beach habitats, demonstrating its importance in optimising their capture success rate. Generally, there are three foraging modes were observed as employed by shorebirds; superficial pecking, medium probing and deep probing (Jing et al., 2006; Zhang et al., 2022). The superficial peck involves inserting a quarter of the bill into the sediment surface, while the medium probe

entails inserting the entire beak into the sediment. During deep probing, the shorebirds immerse their heads deeply into the mud or shallow water. Bar-tailed Godwits usually use tactile stimuli, plunge their straight bills rapidly deep into the sediment, almost invariably vertically downwards close to their feet (Davidson et al., 1986). This allows them to use a variety of sediments from soft muds to firm sands. After capturing, the bird shook the prey, washed it in shallow water (two or three times) and then swallowed it. However, contrary to these techniques, the current study observed 207 individuals of Bar-tailed Godwit exhibiting two modes of uncommon foraging behaviour resembling continuous stitching on sandy beaches. During this mode of foraging, the birds consume prey immediately without first washing it. Occasionally, they ingest water from the waves along with the prey, presumably to reduce friction while transporting it through their straight beaks.

The study also uncovered variations in the capture success rate of Bar-tailed Godwits across the specified sites. Among the study areas chosen, two sand beaches (Ariyallur beach and Pulimoodu beach) were located adjacent to KVCR, a significant wintering and stop-over sites for migrant shorebirds on the west coast of India. These habitats served as alternate foraging grounds for shorebirds from KVCR during high tide hours. Additionally, recent observations indicate an increasing tendency among shorebirds from KVCR to use sand beaches as significant foraging and roosting areas during both tidal phases. This change can be linked to several factors, particularly prey depletion (Aarif et al., 2021a) and the degradation of substrate quality (Rubeena et al., 2023), which affect the availability and accessibility of primary prey items in the KVCR mudflats. Shorebirds, including Godwits exhibit a preference for areas with abundant prey availability (Spruzen et al., 2008). Furthermore, it is observed that Godwits are expected to maximise their prey consumption rate by actively choosing high quality foraging grounds (Evans, 1976). Despite facing heightened predation pressure and human induced impacts, Bar-tailed Godwit exhibited the highest rate of successful prey consumption at

Pulimoodu and Ariyallur sand beaches, in the vicinity of KVCR (Figure 11c), over multiple years (Figure 20). Conversely Kappad beach, with minimal predation pressure exhibited the lowest rate of successful prey consumption rates. This contrast may be explained by the abundance of benthic invertebrates and higher primary productivity in nearshore coastal environments linked to estuaries and intertidal mangroves (Braga et al., 2024; Burford & Faggotter, 2021). Furthermore, they tend to select the riskier habitat since the individuals were unable to achieve their energy requirements in the safer habitat (Yasué et al., 2003). Thus, the benefit of better foraging opportunities outweighed the risk of selecting more dangerous areas (Duijns et al., 2009).

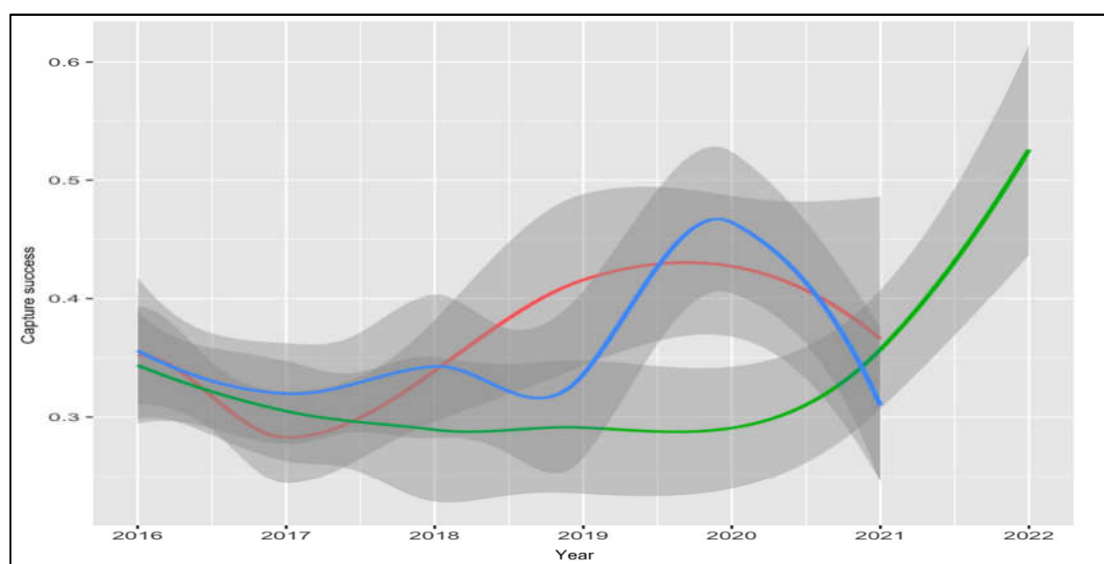


Figure 20. The variation in capture success rates of Bar-tailed Godwits across different habitats over the years. Specifically, the blue, red and green lines indicate data from Ariyallur, Pulimoodu and Kappad sites respectively spanning from 2016-2022. Notably, there is no documentation of this species in 2022, except at the Kappad.

This is further supported by the temporal fluctuations in capture success rates (Table 7 & 8), showing a notable rise in 2022 compared to previous years (Figure 11a). This may be a result of variation in habitat use patterns of shorebirds over the years with a gradual total reliance on sand beaches to meet their high energy requirements. Previous long-term observations conducted along the west coast of India had reported a trend of delayed departure in the northward migration of shorebirds over years (Aarif et al., 2021a). This can provide an insight into the

adoption of the uncommon foraging strategy in this study. Such behavioural adjustments, preferring foraging success over predation risk, were observed in a subspecies of Bar-tailed Godwit, who failed to reach the threshold nutrition level to facilitate their migration in time (Duijns et al., 2009).

In contrast with the ample and diverse macrobenthic invertebrates found in KVCR mudflats and mangroves, sand beaches provide *Cosmonotus* crab as the predominant prey, while other prey items are limited in both abundance and accessibility. It is well-established that larger shorebirds, like the Bar-tailed Godwit exhibit a preference for larger and more profitable prey in their wintering grounds (Choi et al., 2017), employing a combination of pecking and probing techniques (Van de Kam et al., 2017). Probing consists of inserting the bill into the sediment, allowing the capture of infaunal prey and can cost more than pecking in terms of time and energy (Gerritsen & van Heezik 1984). Probing may appear more rewarding in terms of success rate on profitable prey than pecking because of the higher prey availability potential within the extended search depths (Myers et al., 1980; Mouritsen & Jensen 1992). In the sand beach, Bar-tailed Godwits preferred to forage in the wettest areas where the substrate was relatively soft than in adjacent dry areas (Finn, 2009). However, sand beaches, unlike intertidal mudflats have lower sediment penetrability, which can significantly raise the energy costs or the risk of physical damage to the bills of probing shorebirds (Cai et al., 2023). The bill wear is the typical topic of trade-offs (cost benefit). If rewarding (energy intake - energy spent for bill fix up) at sandy areas is higher than muddy areas, the bird should use sandy areas more than muddy areas. Also, prey items may be hidden and/or vertically mobile at depths, often causing capture failure (Kuwaie, 2007). Therefore, to compensate for the reduced intake rate in such habitats, shorebirds prefer to include smaller, less profitable prey alongside larger ones typically sought through probing. According to Dann (2014), the availability of prey outweighs its energy value in determining the foraging preferences of larger shorebirds. This

compensatory strategy may also drive by decreased prey diversity and constraints associated with consuming prey in sand beaches, including heightened predation pressure and wave disturbance. These factors might have contributed to the emergence of an uncommon continuous stitching behaviour. This adaptive response, observed in Bar-tailed Godwits on sand beaches, may opportunistically prioritize small prey profitability. The heightened vulnerability to kleptoparasitism or prey loss during tidal movements, coupled with longer handling times of larger prey might also influence the adoption of this foraging strategy on sand beaches. The absence of a single record of this stitching behaviour in shallow water, on both mudflats and mangroves in KVCR, lends additional credence to this observation. The present findings truly underscore the significance of this compensatory behaviour, as the stitching behaviour proved more successful than typical foraging methods of Bar-tailed Godwits on sand beaches.

Consequently, continuous stitching behaviour seems to be an effective strategy for Bar-tailed Godwits to maximize prey capture while conserving both time and energy, in an unfavourable habitat setting. Interestingly, most instances of this stitching behaviour observed in present study, were associated with either *Cosmonotus* crabs or other small crabs. Generally, the tactile foraging shorebirds had a positive correlation with infaunal however a negative one with epifaunal life forms on sand beaches (Jing et al., 2006). This marks the present finding particularly noteworthy, as Bar-tailed Godwits in the study area explored prey items at various levels of substratum including the epifaunal diversity, which is otherwise favoured by visual foragers. This broader exploration may be explained by the distribution of the various size ranges of *Cosmonotus* crabs throughout the sediment from upper layers to extended depths in the sand beaches along south-west India. Additionally, optimal foraging theory may predict that animals would forage opportunistically when food resources are abundant. The present study

demonstrated that, smaller sized *Cosmonotus* crabs and other small crabs are particularly explored using stitching behaviour on sediment surface, as they are available in the upper most segment of the sediment. The deep mode of stitching behaviour, accompanied by immediate withdrawal from the sediment is completed within 3 to 4 seconds, consuming medium sized *Cosmonotous* crabs and other prey items. Occasionally, they consume larger sized *Cosmonotous* crabs within 6 to 8 seconds from further deeper layers of sediment while continuous stitching.

Two types of stitching behaviours were documented: one involves continuous stitching in a straight-line, while the other entails a wide zigzag pattern of continuous stitching. Both modes were employed alternately, with the latter being more prevalent (Figure 11d). It was noted that a greater number of prey were consumed when the zigzag mode of foraging was adopted (refer to Table 9 & Figure 21), and the trend is increasing over the years (Figure 22). The zigzag mode of foraging is resorted to when the density of prey is more, which strengthens the optimal foraging theory, as birds can consume more prey while covering less distance. The observation that Godwits make their movement decisions not only in response to their immediate foraging success, but also based on their prior knowledge of prey distribution pattern (Dias et al., 2009), demands further investigation on the age-specific employment of both modes of continuous stitching. *Cosmonotus* crabs constituted the most consumed prey, through both zigzag (76.12%) and straight-line mode (72.06%) of foraging (Table 9).

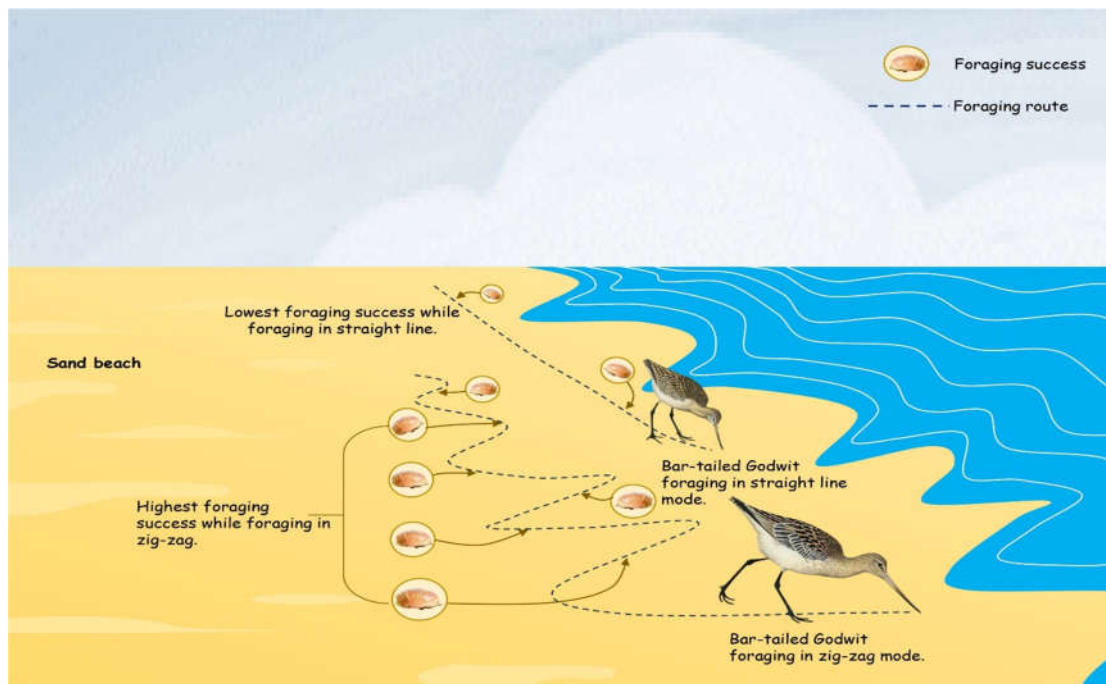


Figure 21. Straight-line and zigzag mode of foraging behaviour exhibited by Bar-tailed Godwit along the sand beaches and associated variation in foraging success.

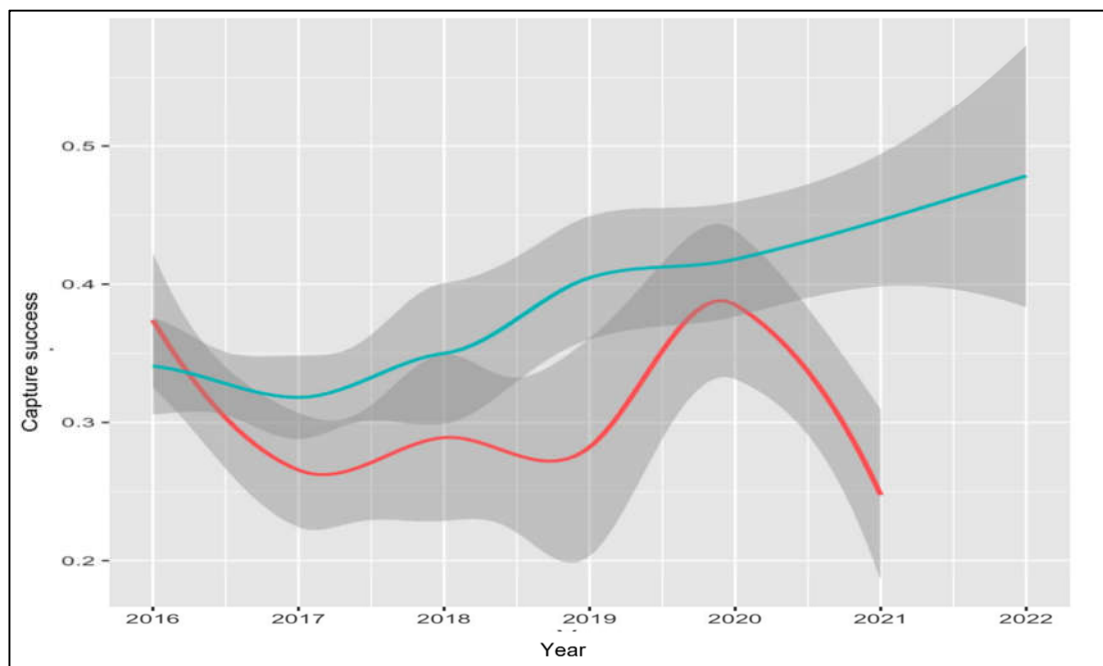


Figure 22. The variation in capture success rate exhibited by Bar-tailed Godwit while employing zigzag mode (Blue line) and straight-line mode (Red line), over the years between 2016-2022. Notably, there is no documentation of the straight-line mode in 2022.

Prey availability to predators is the standard against which the predators' apparent preferences are being judged (Backwell et al., 1998). Besides being abundant, the soft carapace of *Cosmonotus* crab serves as an advantageous factor, reducing the costs associated with handling prey. The study found that the Bar-tailed Godwit consume the larger sized *Cosmonotus* crabs within 6 to 8 seconds (average length of carapace: 41mm) whereas, it takes 36 to 90 seconds to consume the crab species *Scylla oliveacea* (average length of carapace: 61.2mm). Additionally, there is a year-round recruitment of *Cosmonotus* crabs due to their continuous breeding behaviour along the Kerala coasts (Ansell et al., 1972). Therefore, *Cosmonotus* crabs of all age groups (Varying size ranges) were available throughout the year in these habitats. Along with this, the analysis of nutrient quality indicates that the *Cosmonotus* crabs contain higher level of carbohydrates compared to the other prey species (Aarif, unpublished information). Previous studies have also noted similar carbohydrate-rich food consumption by Godwit species in their wintering grounds, occasionally diverging from their carnivorous behaviour to herbivory (Lourenço & Piersma, 2008). While carbohydrates typically suffice for short-distance flights, they can be converted into lipids, which serve as the preferred metabolic fuel for migration (Guglielmo, 2010). Bar-tailed Godwits, renowned for their multi-day non-stop flights, rely exclusively on their body energy stores, primarily composed of lipid reserves. However, the synthesis of energy-dense lipids from carbohydrates occurs exclusively under conditions of carbohydrate surplus. Initially incoming carbohydrates are directed towards glycogen storage, a negligible energy reserve insufficient for sustaining migratory shorebirds (Landys et al., 2005). This may also explain the uncommon continuous stitching behaviour observed, which is aimed at optimizing consumption of carbohydrate-rich *Cosmonotus* crabs to compensate for the lack of direct lipid reserves from other less available prey species. Furthermore, the findings reveal a notably higher capture success rate during October and February, contrasted with a steep decline during March, preceding migration (Figure 8b).

Niche partitioning and diet spectrum of Eurasian Curlew and Bar-tailed Godwit

The Eurasian Curlew and Bar-tailed Godwit are opportunistic feeders consuming a broad range of macrobenthos such as annelids, arthropods, crustaceans, and mollusks (Jiguet et al., 2021). Benthic organisms are distributed throughout intertidal sediments of KVCR, with the larger and more profitable prey found deeper and the smaller prey occurring closer to the surface (Aarif et al., 2021a). This study suggests niche partitioning between Bar-tailed Godwits and Eurasian Curlews, with Godwits favoring mangrove habitats and Curlews preferring sand beaches. These habitat preferences likely align with their morphology and prey selection strategies. Bar-tailed Godwit possesses a straight bill, mechanically optimized for rapid probing in various substrates, from soft mud to firm sand (Davidson et al., 1986). However, this rapid plunging behaviour can damage the sensory receptors at the tip of their beak, hindering their ability to forage effectively in hard sediments. This made them forage mostly in the water column or wet sediment in mangroves. The mangroves that remain wet during low tides and have a greater abundance of epibenthic prey items were thus confirmed to be the perfect habitat for Godwits. It was documented that, Bar-tailed Godwit employing an unusual foraging mechanism in the adjacent sand beaches of KVCR, prefers to forage along the tidal line with wet sediments (Athira et al., 2024c). The inability to forage in soft muddy habitats with their decurved bill might have limited the Eurasian Curlews from foraging at mangroves and mudflats.

While both species exhibited some dietary overlap due to their opportunistic feeding, the low overall dietary similarity (Figure 13) strengthens the argument for niche partitioning. Polychaetes and small crabs were the most frequently captured prey items of Bar-tailed Godwits (Figure 23). The relatively limited constraints for obtaining and consuming medium and small-sized epibenthic prey might have contributed to this trend. This is further supported by their preference to capture deep burrowing polychaetes from the wet and permeable sediments of mangroves and the preferred consumption of epibenthic crabs from the less permeable sediments of mudflats. It was known that the KVCR mudflats had experienced high

sand deposition in recent years (Aarif & Musammilu, 2018), which changed the sediment's permeability and prey availability.

Small fishes and *Cosmonotus* crabs are the most captured prey by Eurasian Curlew (Figure 23). Their large body size necessitates deeper probing for profitable prey in mudflats or mangroves. However, their decurved bill is structurally weaker than an equivalent straight one and so cannot be pushed into firm substrates of mudflats. Therefore, they typically feed by slowly dipping their downward-curving beak into the mud as a habitual strengthening mechanism to handle the intense stresses placed on the beak (Davidson et al., 1986). However, this study found that Eurasian Curlews primarily frequented sandy beaches to consume the readily available *Cosmonotus* crabs, possibly because the relatively short handling time with high energy gain is profitable for shorebirds. At sand beaches, they prefer to feed near the tidal line, where the *Cosmonotus* crabs emerges during receding tides and the sediment is penetrable. This is further supported by the finding that they prefer aquatic insects in mangroves and small fishes in mudflats, which require minimal substrate penetration.

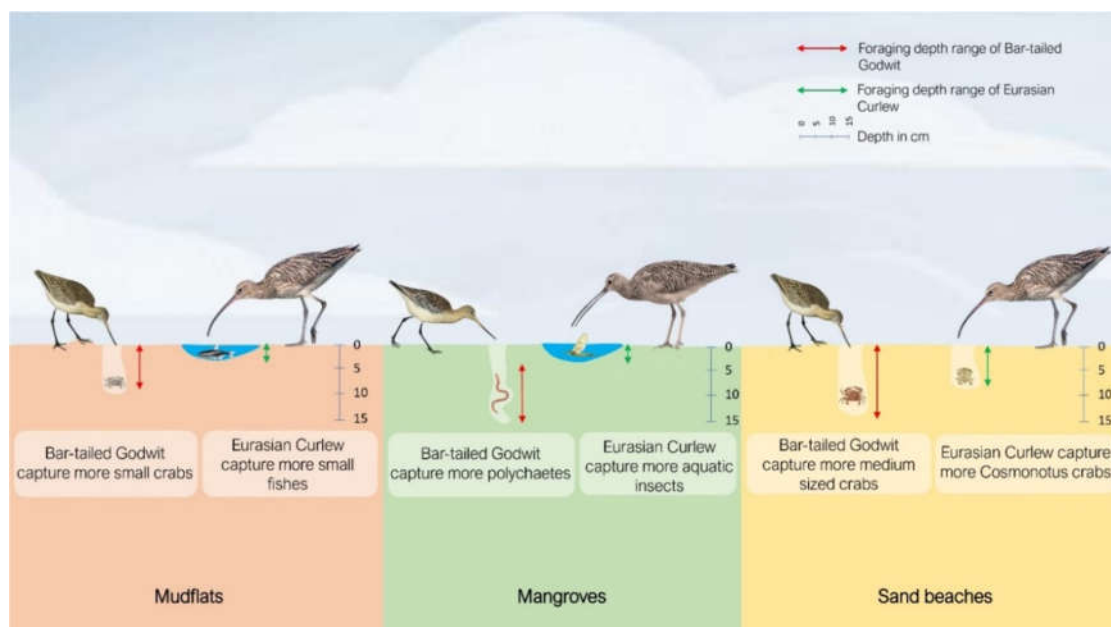


Figure 23. Dietary preferences and niche partitioning of Bar-tailed Godwit and Eurasian Curlew across different habitats - mudflats, mangroves and sand beaches. Bar-tailed Godwit predominantly captures deeply buried prey, while Eurasian Curlew focuses on capturing more epibenthic prey types.

The dietary analysis of droppings collected from Bar-tailed Godwits and Eurasian Curlews across mudflats, mangroves, and sand beaches provide additional insight into their foraging behaviour and habitat use. Seven main prey types were identified: polychaetes, small crabs, medium crabs, shrimp, aquatic insects, *Cosmonotus* crabs, and soft bivalves. In mangroves and mudflats, small crabs emerged as the primary prey for both species, indicating a significant dietary overlap that suggests a shared resource utilization strategy within these habitats. This overlap could potentially lead to competition for resources, especially given the prey depletion observed in these habitats.

On sandy beaches also, there is a potential niche overlapping where, both Eurasian Curlews and Bar-tailed Godwit preferred *Cosmonotus* crabs. This suggests an adaptation to effectively exploit sand beaches due to degraded habitat conditions in mudflats and mangroves (McGuire et al., 2020). Despite severe habitat degradation, high site fidelity among long-distance migrants likely compels them to use suboptimal habitats (Blackburn & Cresswell, 2015). A significant trend is the increasing recruitment of younger shorebirds into agro-ecosystems along the west coast, indicating a higher prevalence of adult shorebirds in coastal habitats. The older age groups select prey like *Cosmonotus* crab, in order to ensure specific nutritional benefits or better meet conditions for optimal foraging due to their abundance or nutritional composition (Johnson et al., 2005). In the face of limited resource availability, which could potentially affect reproductive success, the shorebirds may prioritize most readily available prey to avoid carry-over consequences (Piersma, 2019). The accessibility and lower handling costs associated with foraging on *Cosmonotus* crabs likely compensate for the lack of other prey items. Although further studies are needed to thoroughly understand the energy dynamics and overall foraging efficiency involved.

The shifting foraging patterns toward sand beaches highlight the shorebirds' adaptability but also emphasize the urgency for targeted conservation efforts across different habitats to address their population declines. Additionally, while

droppings analysis provides valuable information on diet structure, it may underrepresent soft-bodied invertebrates (Hira et al., 2020). To gain a deeper insight into dietary shifts and foraging behaviour, complementary approaches such as molecular techniques are recommended. Future research should assess the nutritional quality of various prey items to better understand the prey preferences of these larger shorebirds. Preserving the heterogeneity of microhabitats and diverse prey base at KVCR and adjoining habitats is critical for sustaining shorebird populations under conditions of severe habitat degradation.

Population dynamics of Eurasian Curlew and Bar-tailed Godwit

The analysis reveals a significant and concerning decline in the populations of Eurasian Curlew and Bar-tailed Godwit along the west coast of India. Over the years, both species have shown declining trends, with the highest total population recorded in 2010 and the lowest in 2023 (Figure 15). This trend is indicative of broader issues affecting these species, consistent with other studies highlighting the vulnerability of migratory shorebirds to environmental changes and habitat loss (Duan et al., 2022; Wang et al., 2022; Aarif et al., 2021a; Shamna et al., 2023).

Notably, the highest numbers of both species were observed on sand beaches, based on combined data from Kappad, Ariyallur, and Pulimood sand beaches (Figure 16 & 17). This was unexpected, given that higher abundances were anticipated in mudflats and mangroves, which traditionally provide richer foraging opportunities (Aarif 2009; Meijer et al., 2021). Previous studies have attributed declines in shorebird populations in these habitats to insufficient resources required to meet the energetic demands of migration (Aarif et al., 2021a, 2021b). The foraging habitat switch observed is primarily linked to the availability and profitability of these habitats (Byju et al., 2024). Predation pressure (Aarif & Prasad, 2014) and waste dumping at the mangroves (Aarif, 2009), and sediment hardening and mangrove extension towards the mudflats (Rubeena et al., 2023; Byju et al., 2024), had caused habitat shifts of entire population of shorebirds from mangroves and mudflats to sand beaches.

The KVCR mudflats and mangroves have undergone extensive degradation, including accelerated loss of significant mudflats (Aarif & Musammilu, 2018), deteriorated water and sediment quality (Rubeena et al., 2023), contamination with heavy metals (Aarif et al., 2023) and microplastics (Athira et al., 2024a, 2024b), and declining primary productivity (Athira et al., 2022). These environmental disruptions diminish prey availability (Aarif et al., 2021a) and foraging opportunities for migratory shorebirds. The generalist feeding behaviour of Eurasian Curlews and Bar-tailed Godwits makes them particularly vulnerable to pervasive threats such as microplastics, which further exacerbate their population declines (Athira et al., 2025).



Survival strategies of Bar-tailed Godwit in tropical sand beaches: Straight-line and zigzag foraging techniques

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ABSTRACT

The near-threatened Bar-tailed Godwit (*Limosa lapponica*) makes the longest non-stop endurance flights among shorebirds. They are regular winter visitors to the Kadalundi-Vallikkunnu Community Reserve and adjoining sand beaches along the west coast of India. The research investigates their foraging strategies within sand beaches, observed over six years (2016–2022). Extensive field observations across major sand beaches documented two distinct modes of continuous stitching behaviour; a straight-line mode and a zigzag mode. Despite predation pressure and human disturbances, Bar-tailed Godwits achieved high prey capture rates, likely due to the abundance of benthic invertebrates. The study also revealed the prevalence of this behaviour and its association with rate of prey consumption, particularly focusing on the availability of *Cosmonotus* crabs, the dominant prey species. The zigzag pattern, was associated with higher prey capture rates, suggesting an adaptive response to prey distribution. Our findings suggest that, this unique foraging strategy allows Bar-tailed Godwits to optimize prey capture while conserving time and energy, especially in resource-scarce environments. Furthermore, the implications of these behaviours are discussed in the context of prey availability, nutrient content, and the energetic demands of long-distance migration, shedding light on the adaptive mechanisms employed by shorebirds in challenging habitats.

1. Introduction

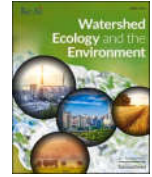
Migratory shorebirds inhabit various habitats globally and demonstrate a broad spectrum of behavioural and ecological adaptations (Koleček et al., 2021; Wang et al., 2022; Angarita-Báez and Carlos, 2023). Long-distance migration is energetically expensive, and time-stressed shorebirds require sufficient resources and must be efficient foragers to satisfy their high-energy demands (Kersten and Piersma, 2002; Estrella et al., 2007). Optimizing foraging strategies for searching and handling food could significantly impact survival of migratory shorebirds. They exhibit opportunistic foraging tactics influenced by beak morphology, prey type and substrate characteristics (Davis and Smith, 2001; Andrei et al., 2009; Angarita-Báez and Carlos, 2023). The foraging behaviour of shorebirds has been widely studied

and different foraging strategies have been well established (Goss-Custard, 1969; Baker and Baker, 1973; Pienkowski, 1978; Puttick, 1979). Understanding feeding specialization is important for evolutionary game theory and the concept of alternate strategies (Smith, 1986). The optimal foraging theory suggests that foraging decisions are based on a maximization of currencies (Stephens and Krebs, 1986; Ydenberg and Hurd, 1998; Bautista et al., 2001). Accordingly, the profitability of prey is determined by a trade-off between handling costs (time, energy & predation) and gross energy gain, influenced by factors such as prey size, nutritional quality and digestibility (Backwell et al., 1998). Foraging success rate plays a crucial role in the geographical distribution, habitat selection, migration and reproductive success of shorebirds. Benthic macroinvertebrates such as polychaetes, crustaceans, and molluscs constitute a major part of the diet of migratory

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Unveiling the diets of Eurasian Curlew and Bar-tailed Godwit through droppings analysis on the west coast of India

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ABSTRACT

This study examines the population dynamics and dietary patterns of the near-threatened Eurasian Curlew and Bar-tailed Godwit along west coast of India, underscoring critical conservation issues. From 2010 to 2023, both species experienced significant declines, with peak abundances observed on sandy beaches, deviating from their usual mudflat and mangrove habitats. Analysing 231 droppings identified seven key prey types, with polychaetes and small crabs being most common in mangroves and mudflats, while *Cosmonotus* crabs were predominantly found on sand beaches. Species-specific prey preferences were evident, with Bar-tailed Godwits showing a significant association with polychaetes and medium crabs. The findings highlight the urgent need for habitat restoration, pollution reduction, and focused conservation efforts to ensure the resilience and survival of these critical shorebird species.

Introduction

Migratory shorebirds (Charadriidae) serve as crucial global indicators for assessing the health of delicate coastal ecosystems (Mathot et al., 2018; Sutherland et al., 2012). Their local distribution is influenced by food availability and feeding adaptations (Fonseca et al., 2017). Given that shorebirds migrate great distances and inhabit various kind of habitats throughout their annual cycle, dietary flexibility is advantageous for exploiting variable resources (Isacch et al., 2005). Shorebirds undertake some of the longest migrations known and are experiencing significant population declines globally (Aarif et al., 2014; 2017; Shamna et al., 2023; van de Pol et al., 2024). Their low reproductive rates and the severe degradation of critical wintering habitats hinder their ability to recover from population declines.

Long-distance migration imposes significant energy costs, necessitating efficient foraging strategies to meet their high-energy demands (Kersten and Piersma, 2002). The quality and diversity of foraging sites during the wintering period directly affect their winter survival, subsequent migration, and breeding success (Jackson et al., 2024). Consequently, the spatiotemporal distribution of shorebirds in intertidal areas

depends on prey diversity, density, and availability to maximize energy intake (Jourdan et al., 2021). Changes in intertidal foraging grounds can impact energy budgets and patterns of abundance and distribution of shorebirds (Calle et al., 2016), potentially affecting species survival. Organisms facing challenges in maintaining a positive energy budget may exhibit coping mechanisms such as spatial adjustments (Piersma, 2012), behavioural modifications (Sydeman et al., 2001), or phenotypic adaptations (Piersma and van Gils, 2011). Specialist species, which have a narrow trophic niche, face particular challenges when food availability varies spatially and temporally, impacting individual survival and population persistence.

Specialization reduces interspecific competition by decreasing niche overlap between species (Chesson, 2000). However, spatiotemporal variations in food availability can influence dietary patterns and species distribution (Hughes, 2000). In this context, intraspecific dietary adjustment, or trophic plasticity, can be advantageous for home range expansion, persistence in human-impacted areas, and population differentiation through local adaptation (Mendes et al., 2009; Michel et al., 2015). Shorebirds exhibit a variety of beak morphologies associated with their foraging strategies and dietary preferences (Gliesch et al.,

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Comparative dietary analysis of Eurasian Curlew *Numenius arquata* and Bar-tailed Godwit *Limosa lapponica* along the west coast of India

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Abstract

This study examined the diet of two near-threatened migratory shorebird species, Eurasian curlew (*Numenius arquata*) and bar-tailed godwit (*Limosa lapponica*), within crucial wintering habitats on India's west coast. These regions have experienced severe declines in shorebird populations due to environmental degradation and prey scarcity. Our research revealed distinct habitat preferences and dietary patterns between the two species, suggesting niche partitioning as a mechanism for coexistence. Bar-tailed godwits primarily inhabited mangroves, where they consume polychaetes and small crabs using their straight bills. In contrast, Eurasian curlews with their curved bills favored sand beaches, feeding on small fishes and mole crabs. While droppings analysis indicated some overlap in prey consumption, especially small crabs in mudflats and mangroves, video observations revealed minimal overall dietary overlap. These findings underscore the significance of habitat diversity and prey abundance at the study site in facilitating niche partitioning and supporting the coexistence of these threatened shorebird species.

Keywords Faecal samples · Niche partitioning · Scolopacidae · Wading birds · Video recordings

Introduction

Migratory shorebirds (Charadriiformes) are vital indicators of coastal ecosystem health (Mathot et al. 2018; Sutherland et al. 2012). Their survival depends on factors like habitat quality, food availability, and human impacts (Jackson et al. 2024). During winter, they primarily consume benthic macroinvertebrates like polychaetes, crustaceans, and mollusks (Placyk and Harrington 2004; Angarita-Báez and Carlos 2024). As top predators of benthic invertebrates, shorebirds regulate prey populations, influencing ecosystem dynamics (Hamilton et al. 2006; Mathot et al. 2018).

Their long-distance migrations require efficient foraging strategies to meet their high-energy demands (Zhao et al. 2017). Previous studies have described and compiled diverse shorebird feeding strategies (Baker and Baker 1973; Angarita-Báez and Carlos 2023a). Distinct correlations exist between bird morphology and foraging habits among shorebird species (Weeks et al. 2020). Some species rely on visual cues and surface pecking to capture prey, while others probe deep into sediments. Additionally, certain shorebirds employ a combination of both strategies (Lourenço et al. 2016; Angarita-Báez and Carlos 2023b).

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CHAPTER 2

THE EXTENT OF HABITAT DEGRADATION AND THE ADAPTIVE FORAGING STRATEGIES OF SHOREBIRDS ALONG THE WEST COAST OF INDIA

Introduction

Coastal ecosystems are undergoing rapid environmental alterations due to the effects of climate change and other anthropogenic stressors. These stressors often interact and leading to bottom-up or top-down regulated trophic cascades, significantly influencing trophic interactions in food webs (Hemraj et al., 2017). Understanding long-term changes in environmental variables such as temperature fluctuations, rainfall patterns and nutrient dynamics is crucial for assessing their impacts on ecosystem functioning. Changes in zooplankton abundance is considered as the rapid and most sensitive response to such shifts in environmental variables in estuarine and coastal ecosystem (Serranito et al., 2016). Variations in zooplankton abundance can significantly influence macrobenthic prey abundance, ultimately shaping shorebird foraging strategies.

Long-distance migrant shorebirds, which rely on diverse habitats for refueling, require specialized morphological and behavioral adaptations to optimize foraging success. Their feeding ecology is shaped by prey availability, substrate conditions, and species-specific foraging techniques. Additionally, prey transport within the bill cavity is a crucial but underexplored aspect of shorebird foraging efficiency.

This chapter aims to provide insights into the adaptive strategies of shorebirds under changing environmental conditions. The study examines the long-term zooplankton abundance trends in response to changes in environmental variables in a key wintering site of shorebirds. Additionally, foot trembling behavior, an adaptation observed in certain shorebirds to enhance prey detection, is explored in relation to substrate conditions. Furthermore, it focuses on diverse prey transport mechanisms, which enhances foraging efficiency across species in the same study sites. Finally, the study investigates the shifts in habitat preferences of shorebirds in response to the environmental changes causing disruptions in optimal refueling.

Historical review

Multiple anthropogenic stressors that often interact with one another are beginning to have large impacts on coastal and pelagic biodiversity (Williamson &

Guinder, 2021). Understanding the structure and functioning of coastal ecosystems and assessing the effects of these stressors remain challenging (Doo, 2020). Climate-driven changes in the open ocean influence species interactions, causing cascading effects on communities, food webs, and ecosystem services (Boyd et al., 2015; Lotze et al., 2019). As a key component of trophodynamics of pelagic ecosystems, plankton represent the first level of integration of hydroclimatic forcing in the food web (Beaugrand, 2005).

Over the last decades there has been a global shift in the zooplankton population (Schmidt et al., 2020). Such shifts are expected to operate differently across ecosystems and must be understood in the context of local oceanography and long-term trends (Ji et al., 2010; Atkinson et al., 2015). Any short- or long-term changes in the physical, chemical or biological attributes is likely to affect the biomass and abundance of both phyto and zooplankton (Sahu et al., 2018). There is a significant knowledge gap on how the environmental conditions can shape and restructure plankton communities in marine ecosystems (Rajkumar et al., 2020; Schmidt et al., 2020).

The Arabian Sea is one of the world's most productive oceanic regions (Prasanna Kumar et al., 2002; O'Mara and Dunne., 2020). The boundary and open ocean processes of the Arabian Sea are influenced by upwelling during summer and cooling in winter that brings up great amounts of nutrients into the upper ocean providing resources for primary producers and ultimately fisheries (Madhupratap et al., 2001; Santhikrishnan et al., 2021). Upwelling and the seasonal reversal in surface circulation during the monsoons cause distinct patterns in nutrient distribution and light penetration, which in turn have important effects on primary production in the Arabian Sea (Sushanth & Rajashekhar., 2014). It is well established that an intense southwest monsoon triggers strong upwelling along the west coast of India, thus making the Arabian Sea along the west coast more productive than the east coast (Rajagopalan et al., 1992; Rajkumar et al., 2020; Santhikrishnan et al., 2021). Consequently, the biodiversity of the west coast of India is richer and more abundant than the east coast (Musale & Desai 2011; Shivaramu et al., 2019; Rajkumar et al., 2020; Santhikrishnan et al., 2021). The

southwest monsoon plays a critical role in altering local environmental features such as water temperature, salinity, dissolved oxygen and nutrients (Rajagopalan et al., 1992; Shivaramu et al., 2019; Rajkumar et al., 2020; Santhikrishnan et al., 2021). The increase in nutrients after the southwest monsoons helps to increase plankton abundance in the west coast of India.

The southwest coast of India appears to be suffering from a significant shortage in rainfall during the monsoon (Aarif et al., 2021a). The shortage of freshwater supply due to the reduction in freshwater input during the monsoon can cause deterioration in the water quality with measurable consequences on biodiversity of the Indian coastal zones (Shivaramu et al., 2019; Santhikrishnan et al., 2021). Regionally there is evidence of a decline in the primary productivity of the Arabian Sea due to deterioration in the water quality of the region (Alcaraz & Calbet., 2003; Piontkovski & Castellani., 2009; Pitchaikani & Lipton., 2016; Capuzzo et al., 2017; Sahu et al., 2018). Pitchaikani and Lipton (2016) showed that nutrient contents determine the primary productivity and plankton diversity of the east coast of India. Severe fluctuations in nutrient supply could cause a reduction in primary production, which can impact the stability and the sustainability of the fish productivity in the area (Santhikrishnan et al., 2021). Such bottom-up shifts have the potential to influence not only predator–prey synchrony but also reproductive success, migration, distribution, abundance and population density of organisms at different trophic levels including shorebirds (Hollowed et al., 2013; Salinger et al., 2013; Schmidt et al., 2020).

Shorebirds exhibit a range of foraging strategies that enable them to exploit diverse prey items available in the dynamic coastal habitat. The foraging ecology of shorebirds is often characterized by food selection, habitat preference, and prey capturing tactics or behaviour employed by them in a particular habitat (Angarita-Báez & Carlos, 2023b; Jackson et al., 2024). The morphology of a bird is considered an important factor in restricting the ranges of foraging techniques it can perform (Yu et al., 2023). The bill length and leg length influence the preference of foraging water depths by shorebirds (Aarif et al., 2024). Benthic macroinvertebrates (e.g., polychaetes, bivalves, and crustaceans) serve as critical, nutrient-rich prey for

migratory shorebird species at coastal or intertidal, stopover and wintering sites (Huang et al., 2022). Many shorebirds detect their prey by probing with their bills in soft ground, by touch, or by sweeping their bills through shallow water (Angarita-Báez & Carlos, 2023b). Others detect their prey by sight, and some use a mixture of visual and tactile cues (Thomas et al., 2006). An evolutionary increase in eye size is predicted to be associated with visual foraging behaviours requiring high spatial resolution and high sensitivity (Thomas et al., 2006). The greater surface activity of invertebrate prey must be particularly important in making them available to those shorebirds, such as the plovers, that are obligate visual feeders and also to those that make use of visual cues. Foot trembling is a mechanism known to be exhibited by visual foraging shorebirds in order to enhance prey detectability by fluttering one foot over the ground at a 90-degree angle to incite invertebrates under substrate. On the other hand, in tactile foragers mechanoreceptors located in the bill skin that convert pressures and vibrations into electric signals allow the location of prey even by remote touching (Baguette et al., 2023).

Prey detectability by visual/tactile foraging shorebirds is influenced by substrate characteristics along with prey activity (Kober, 2004). VanDusen et al. (2012) explained the role of sediment grain size on shorebird feeding distribution, accounting for its influence in prey availability independent of their abundance. The tactile foragers were observed as utilizing habitats with higher silt/clay content, facilitating greater prey availability due to increased sediment penetrability and heightened surface prey activity. On the other hand, the habitats with coarse sediments were better utilized by visual foragers where tactile foragers experience diminished foraging success. A higher frequency of foot trembling behaviour has been observed among visual foraging shorebirds in sandy beach habitats (Angarita-Báez & Carlos, 2023b).

The ability of shorebirds to track environmental changes and optimize their foraging strategies is critical for meeting the energetic demands of migration. While extensive research has examined the effects of foraging techniques such as pecking and probing on prey capture efficiency, the mechanisms of prey transport within the bill cavity remain understudied. Efficient prey transport can minimize handling

time, a key factor influencing overall foraging success. Rubega and Obst (1993) identified a novel feeding mechanism, surface tension transport, in the Red-necked Phalarope (*Phalaropus lobatus*), wherein the surface tension of water surrounding prey facilitates movement from the bill tip into the mouth. Subsequent laboratory experiments by Rubega (1997) demonstrated that this ability extends to other shorebirds with needle-shaped bills, including Wilson's Phalarope (*Phalaropus tricolor*), Western Sandpiper (*Calidris mauri*), and Least Sandpiper (*Calidris minutilla*).

Although these experimental studies suggest that surface tension transport may be more widespread among shorebirds, field-based evidence remains limited. A preliminary study by Estrella et al. (2007a) in a Spanish salt pan provided the first field observations of this mechanism in species such as the Little Stint (*Calidris minuta*), Dunlin (*Calidris alpina*), Sanderling (*Calidris alba*), Curlew Sandpiper (*Calidris ferruginea*), Common Redshank (*Tringa totanus*), and Black-winged Stilt (*Himantopus himantopus*). The mechanical basis of surface tension transport was further elucidated in laboratory conditions by Prakash et al. (2008). Additionally, Estrella and Masero (2007b) reported the occurrence of distal rhynchokinesis—a mechanism that enhances small prey profitability, in species such as the Dunlin, Curlew Sandpiper, Sanderling, and Little Stint.

Despite these findings, comprehensive assessments of diverse prey transport mechanisms remain scarce, particularly within the Central Asian Flyway (CAF). The prevalence and ecological significance of these mechanisms in natural shorebird populations, especially in degraded habitats, remain largely unexplored.

Among the pivotal strategies by which animals adapt to the challenges of habitat degradation, exploring alternate habitats emerges as a crucial mechanism. Over-summering is a phenomenon observed in migratory bird populations, where certain individuals forgo migration (Tavera et al., 2020). During this extraordinary occurrence, young birds, occasionally accompanied by solitary adults, elect to remain in non-breeding grounds while the bulk of the population migrate back to their breeding grounds. The phenomenon has been documented across 15

different bird families, with a notable prevalence among shorebirds (Wille & Klaassen, 2022). Over-summering shorebird populations may also include adults in poor condition, unable to meet the energetic demands and risks of migration (Vieira, 2016). Although, one-year-old shorebirds exhibit an elevated tendency for over-summering across various documented species (Martínez-Curci et al., 2020). Understanding the spatiotemporal dynamics of over-summering shorebird populations is crucial to directing extensive conservation efforts towards these migratory species.

The Kadalundi-Vallikkunnu Community Reserve (KVCR) on the west coast has been supporting a significant number of both wintering and over-summering shorebirds (Aarif et al., 2011, 2020). Although, a previous long-term study showed a decline in over-summering shorebird abundance in KVCR (Aarif et al., 2020), little is known about the demographic composition and distribution patterns of shorebirds within KVCR and its adjoining habitats. Identification and preservation of over-summering areas will benefit the survival rates of adults that postpone migration during a given year, in addition to their critical role in influencing the recruitment rate of long-distance migratory species during ontogeny (Navedo & Ruiz, 2020). To accurately determine the significance of agroecosystems as essential alternate habitats, Byju et al. (2024) emphasized the need for systematic investigations of over-summering shorebird population dynamics in addition to studies of wintering populations.

Results

Long-term changes in environmental variables and its impacts on zooplankton communities

Changes in water variables over years

Water variables varied significantly from 2010 to 2019 (Figure 24). In fact, inversely to water phosphate that showed a significant increase ($F_{9, 950}=12.66$, $p<0.001$) (Figure 24f), water nitrate ($F_{9, 950}=12.47$, $p<0.001$) (Figure 24e) and water chlorophyll (Figure 24g) ($F_{9, 950}=8.76$, $p<0.001$) decreased significantly over years. Likewise, water temperature ($F_{9, 950}=92.07$, $p<0.001$) (Figure 24b), water salinity

(F9, 950=18.84, $p<0.001$) (Figure 24c) and water pH (F9, 950=26.06, $p<0.001$) (Figure 24d) increased significantly between 2010 and 2019.

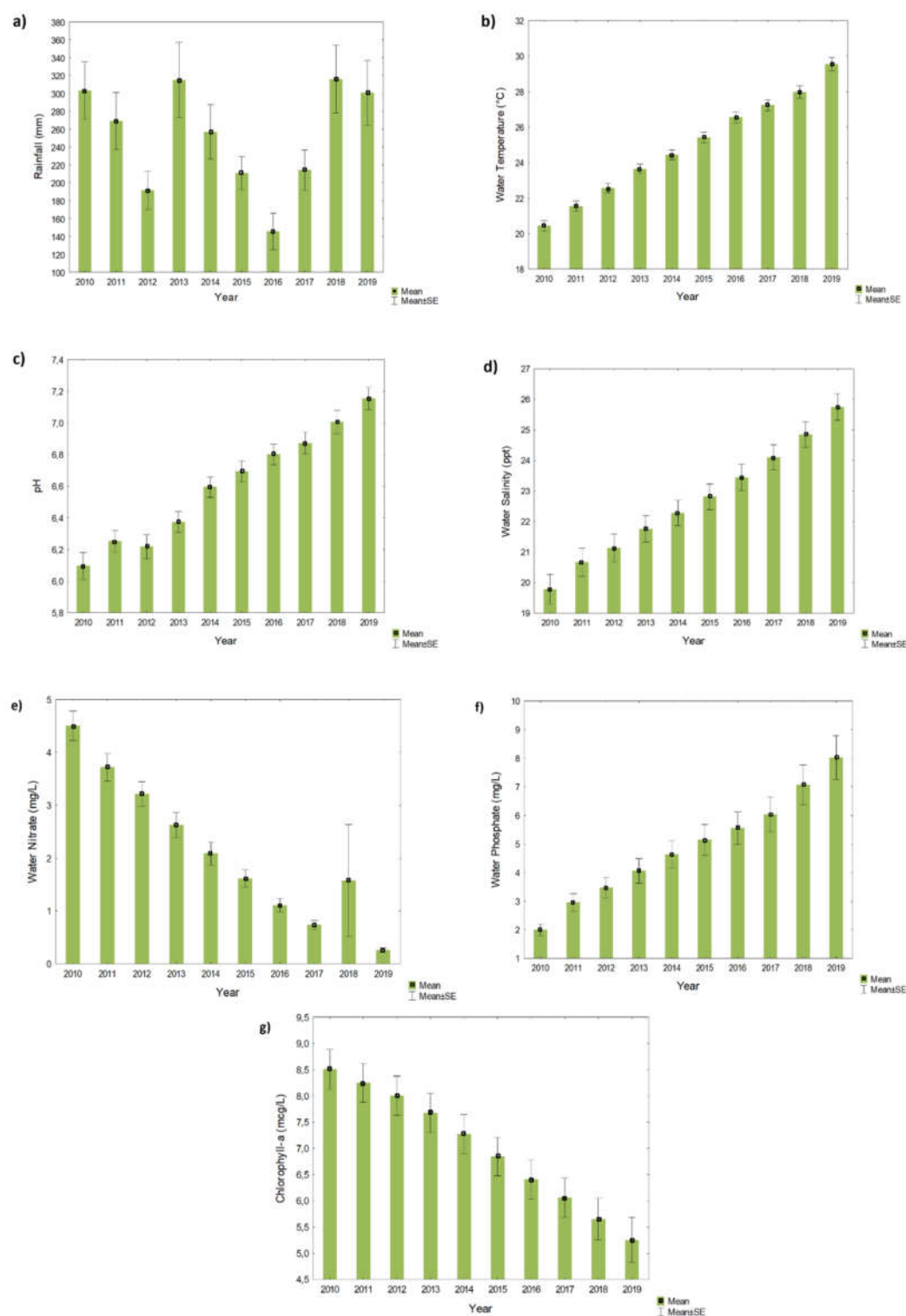


Figure 24. The variation of environmental variables; **(a)** rainfall, **(b)** water temperature, **(c)** pH, **(d)** water salinity, **(e)** water nitrate, **(f)** water phosphate, **(g)** chlorophyll-a, over the years between 2010-2019.

Environmental factors influencing zooplankton density

Three factors (habitat, season and year) and five covariates (Water Temperature, Water Salinity, pH, Water Phosphate and Chlorophyll a) were retained in most parsimonious model explaining changes in zooplankton density (Table 12). This parameter decreased significantly over years from 2010 (22.81 ± 1.07) to 2019 (13.46 ± 0.78) (Figure 25a). Zooplankton density varied significantly over seasons and habitats (Table 13). Highest values were recorded during dry season (18.41 ± 0.40) (Figure 25b) and in mangroves (25.63 ± 0.79) (Figure 25c) while lowest zooplankton density was revealed during wet season (16.40 ± 0.32) and at beaches (15.62 ± 0.25). Zooplankton density decreased significantly with increasing salinity and phosphate in water (Table 13). However, water temperature, pH and chlorophyll density influenced zooplankton density positively (Table 13).

Table 12. General Linear Models showing a summary of models for measures of zooplankton abundance (response variable) in surveyed at coastal habitats of west Coast of India (Tp: Water Temperature, Sln: Water Salinity, pH: Water pH, Nt: Water Nitrate, Phs: Water Phosphate, Chl: Chlorophyll a).

Explanatory variables	k	AIC	AIC wi
Tp+Sln+pH+Phs+Chl+Habitat+Season+Year	9	5173.25506	0.6962867
Tp+Sln+pH+Nt+Phs+Chl+Habitat+Season+Year	10	5174.91441	0.3037133

Table 13. Variables significance on zooplankton abundance on the top model (Tp: Water Temperature, Sln: Water Salinity, pH: Water pH, Nt: Water Nitrate, Phs: Water Phosphate, Chl: Chlorophyll a).

Response variable	Explanatory variables	df	F	p	Estimate	SE
Zooplankton abundance ($R^2 = 0.46$)	Intercept	1	2.7934	0.192596	-28.4938	3.101893
	Water Temperature	1	137.731	0.000000	1.0931	0.093139
	Water Salinity	1	7.6667	0.005735	-0.168	0.060674
	pH	1	17.2802	0.000035	1.5731	0.378416
	Water Phosphate	1	46.6537	0.000000	-0.5865	0.085866
	Chlorophyll-a	1	38.7989	0.000000	0.454	0.072889
	Habitat	2	167.9491	0.000000		
	Season	1	17.3875	0.000033		
	Year	9	25.5869	0.000000		
	Error	942				

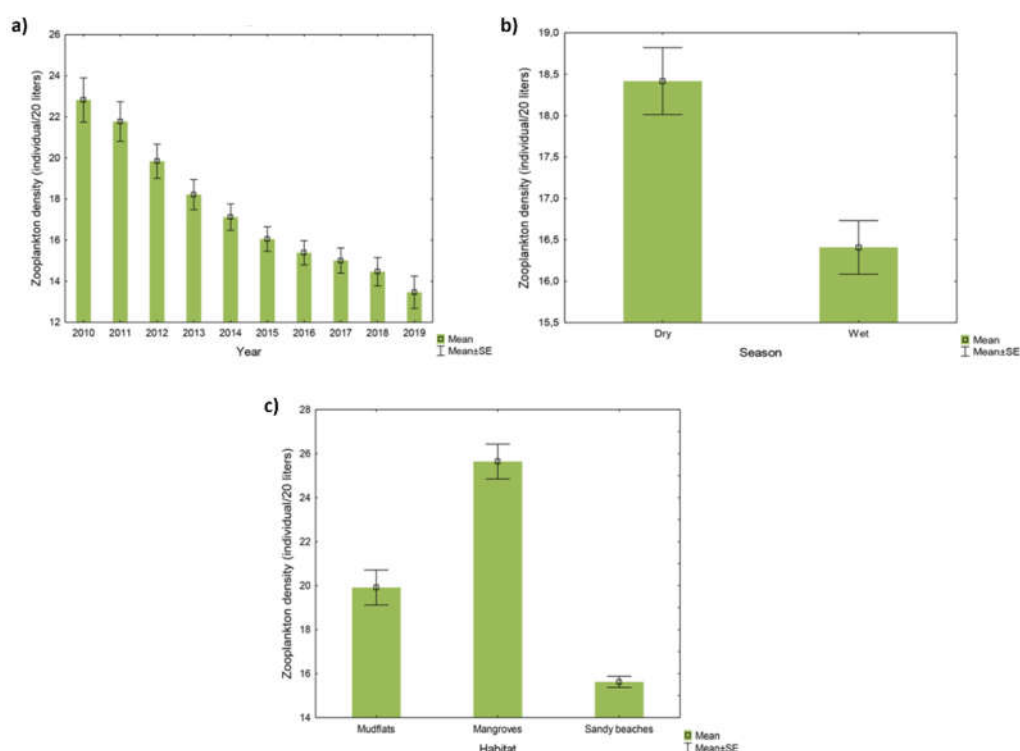


Figure 25. Variation in zooplankton abundance over- **(a)** years, **(b)** seasons and **(c)** habitats.

Adaptive behavioural strategies of shorebirds in altered foraging habitats

Widespread occurrence of foot trembling behaviour across the species

The study encompassed an analysis of foot trembling behaviour in seven species of shorebirds across two distinct microhabitats (Mudflats & Mangroves) over multiple years between 2010-2019. Results obtained through chi-square analysis revealed statistically significant p-values ($p < 0.05$) for the majority of the investigated species, with Common Greenshank emerging as a notable exception to this observed trend (Table 14).

Among visual foragers, there is no consistent pattern in the frequency of exhibition of foot trembling activity was noted. In mudflats and mangrove habitats, the Tibetan Sand Plover experienced contrasting trends in foot trembling behaviour. In mudflats, it showed an increase after 2014 followed by a decline in 2018, whereas in mangroves, it exhibited a decline post-2014, reaching a peak in 2018 (Figure 26a & 26b). Similarly, the Greater Sand Plover displayed different patterns in mudflats compared to mangroves. In mudflats environments, it demonstrated a pronounced increase in foot trembling behaviour after 2014, while in mangroves, the steep

decline post-2014 was followed by a relatively stable trend (Figure 26c & 26d). For the Pacific Golden Plover, its behaviour differed between the two habitats as well. In mudflats, it displayed fluctuating yet relatively higher levels of foot trembling activity compared to its behaviour in mangroves (Figure 26e). In mangroves, it maintained consistently low levels of foot trembling activity, with an exceptional increase in 2017 (Figure 26f).

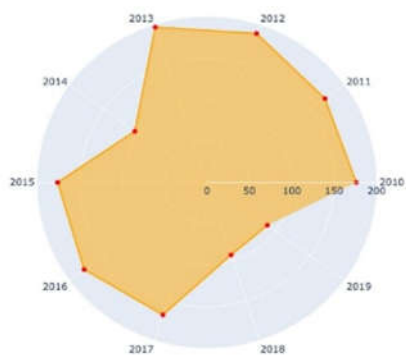
Tactile foragers displayed no significant difference across microhabitats or temporal scales. Over the study period, foot trembling occurrence in the Terek Sandpiper remained fluctuating yet consistently high in both habitats (Figure 26g & 26h). Similarly, the Sanderling exhibited parallel trends in both the habitats, with a notable increase observed after 2015 (Figure 26i & 26j).

Notably, opportunistic foragers displayed diverse patterns: the Common Redshank demonstrated a much higher trend in foot trembling occurrence across the years in mudflats particularly after 2013. In mangroves, they exhibited a comparatively lower and stable trends (Figure 26k & 26l). On the other hand, the larger sized Common Greenshank showed stable and significantly higher occurrence of foot trembling in mangrove habitats, but notably lower yet stable occurrence at mudflats, except for a peak during 2011 (Figure 26m & 26n).

Table 14. Results of chi-square test conducted among the seven selected shorebird species across mudflats and mangroves over consecutive years.

Species	Foraging mode	Microhabitat	<i>p</i> Value
Tibetan Sand Plover	Visual	Mudflats	0.000
		Mangroves	0.000
Greater Sand Plover	Visual	Mudflats	0.000
		Mangroves	0.000
Pacific Golden Plover	Visual	Mudflats	0.000
		Mangroves	0.000
Sanderling	Tactile	Mudflats	0.003
		Mangroves	0.124
Terek Sandpiper	Tactile	Mudflats	0.048
		Mangroves	0.100
Common Redshank	Opportunistic	Mudflats	0.000
		Mangroves	0.000
Common Greenshank	Opportunistic	Mudflats	0.012
		Mangroves	0.773

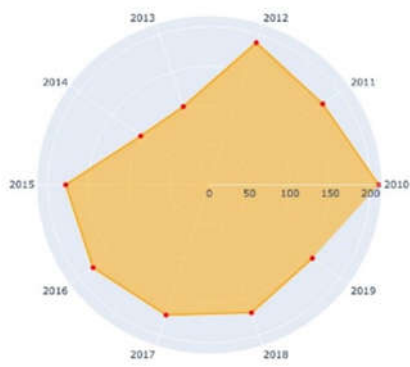
a)



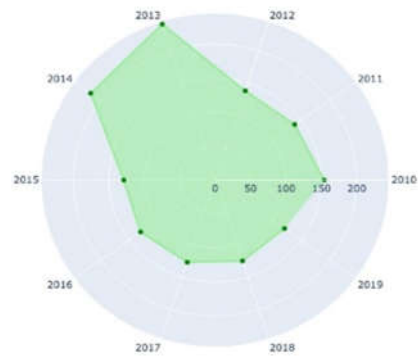
b)



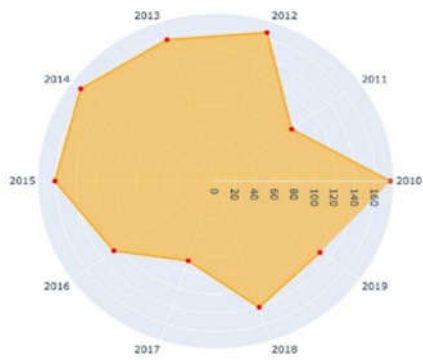
c)



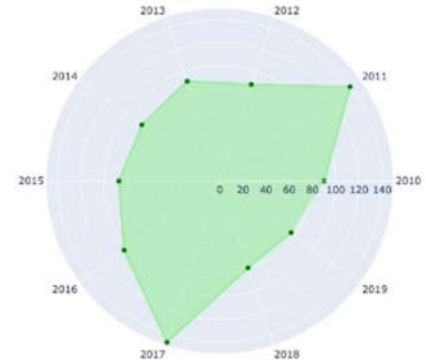
d)



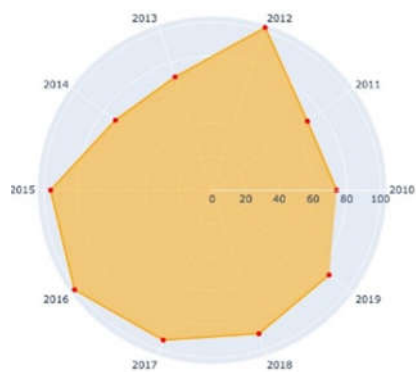
e)



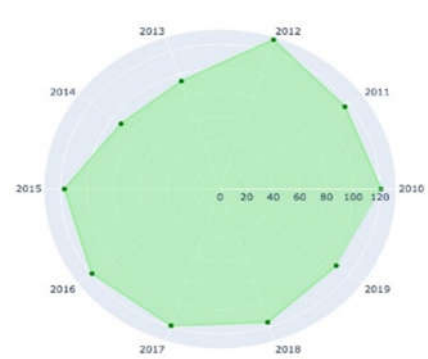
f)



g)



h)



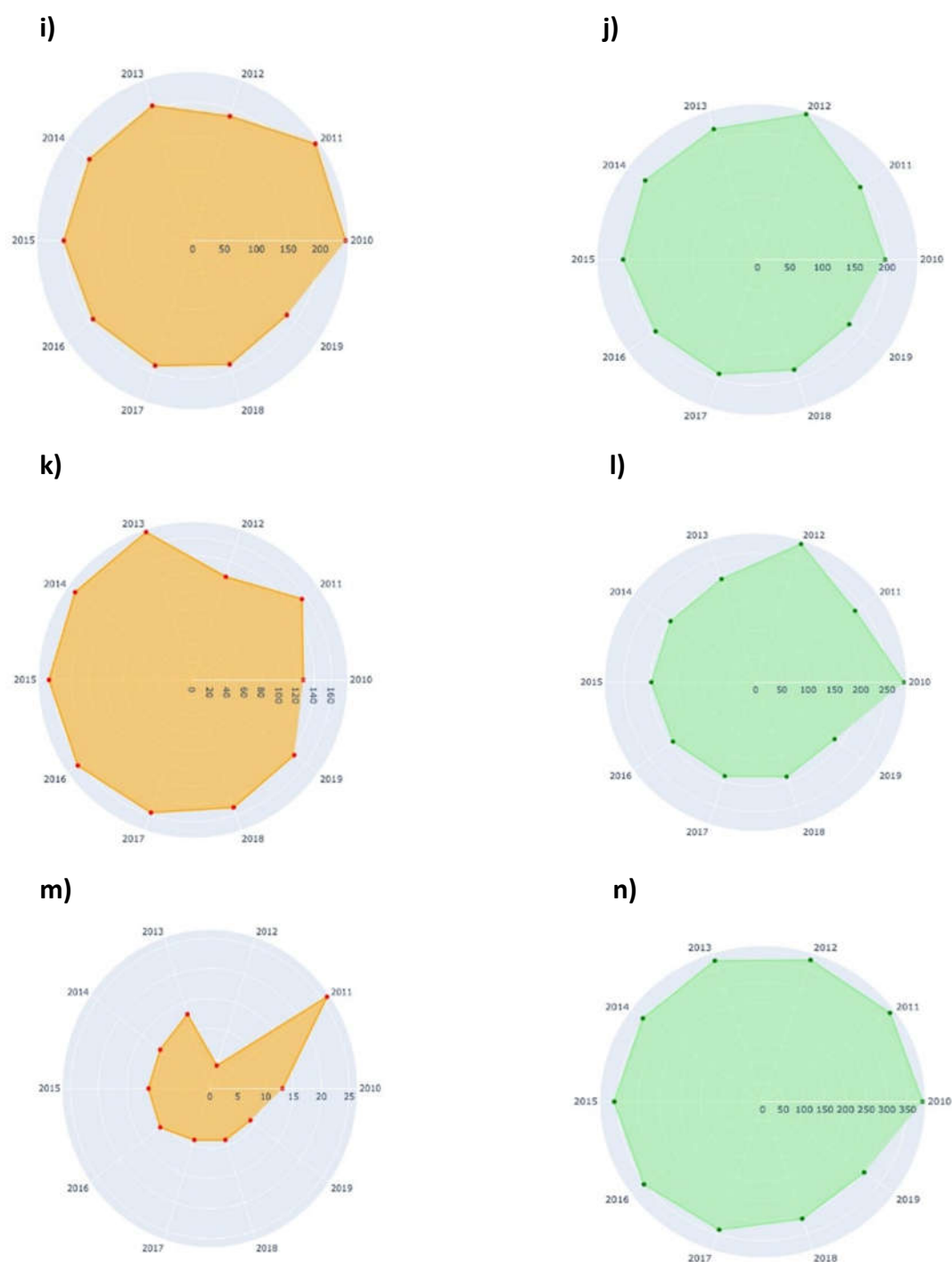


Figure 26. Radar charts illustrating the frequency of foot trembling behaviour exhibited by the seven species of shorebirds across years in mudflats (Saffron) and mangroves (Green) of KVCR. (a) & (b) Tibetan Sand Plover, (c) & (d) Greater Sand Plover, (e) & (f) Pacific Golden Plover, (g) & (h) Sanderling, (i) & (j) Terek Sandpiper, (k) & (l) Common Redshank and (m) & (n) Common Greenshank.

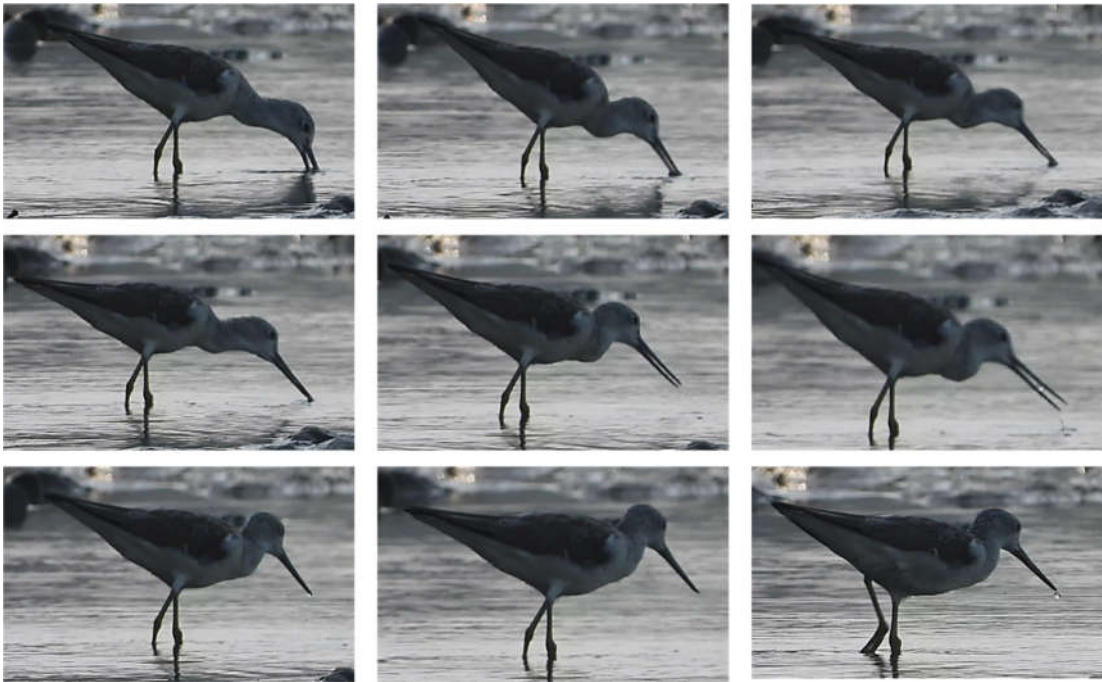
Different prey transport mechanisms across species in the degraded mudflats

All observed species at KVCR exhibited cranial kinesis, characterized by the independent elevation of upper jaw during prey capture and handling. This trait, inherited from their reptilian ancestors, is highly developed in shorebirds and facilitates specialized feeding strategies. Three distinct prey transport mechanisms enabled by cranial kinesis were identified, differing based on bill morphology, prey size and feeding microhabitat.

Surface tension transport

Medium sized shorebirds employed surface tension-based prey transport when consuming microscopic prey suspended in the water column. This mechanism was observed in straight, pointed-billed, opportunistic feeders such as Common Greenshank and Common Redshank. Water droplets containing invisible prey were rapidly transported along the beak through a tweezing motion, characterized by rapid opening and closing of the beak. After prey ingestion, the remaining water was expelled using the same mechanism (Figure 27a & 27b).

a)



b)



Figure 27. Medium sized shorebirds employing surface tension-based prey transport in water column: **(a)** Common Greenshank and **(b)** Common Redshank.

Water-dependent inertial transport

This mechanism was observed in the Grey Plover when handling small but visible prey items from the water column. Unlike surface tension-based prey transport, which relies on surface adhesion forces, this method involved rapid beak movements and controlled water intake to facilitate the prey transport. The ingested water was subsequently expelled following prey capture and ingestion (Figure 28).



Figure 28. Water-dependent inertial transport employed by Grey Plover to consume small invertebrate prey in water column.

Distal rhynchokinesis in larger shorebirds

Larger shorebirds, such as Bar-tailed and whimbrel, employed distal rhynchokinesis when capturing and transporting larger invertebrate prey from the mudflats. During prey capture, the distal part of the upper jaw flexed downward, securing the prey at the bill tip (Figure 29). As the prey was transported, the tip of upper jaw elevated, ensuring a controlled movement toward the mouth.

a)



b)



Figure 29. Distal rhynchokinesis employed while capturing larger invertebrate prey from dry sediment in mudflats by **(a)** Bar-tailed Godwit and **(b)** Whimbrel.

Habitat transitions- increasing recruitment of over-summering younger shorebirds to agroecosystems

The total abundance of shorebirds, and the abundance of immature shorebirds visiting the coastal areas region (three habitats combined: mudflats, salt pan and

sand beaches), significantly decreased from 2016 to 2023 (Table 15 & Figure 30). Conversely, in agricultural areas region (habitat: agricultural land), the total abundance and the abundance of immature shorebirds exhibit an increasing trend during this period. Nevertheless, in both the habitats, the abundance of adult shorebirds remains constant.

Table 15. Annual variation in the abundance (mean $\pm$ SD) of immature, adult and overall shorebirds across different habitat types.

Year	Habitat type	Immature shorebirds	Adult shorebirds	Overall Shorebirds
2016	Mudflats	118 $\pm$ 29	15 $\pm$ 6.5	133 $\pm$ 35.5
2016	Sand beaches	148 $\pm$ 40.5	15 $\pm$ 4	163 $\pm$ 44.5
2016	Salt pan	118 $\pm$ 28	14 $\pm$ 8.5	132 $\pm$ 36.5
2016	Agricultural land	57 $\pm$ 6.04	21 $\pm$ 2.76	78 $\pm$ 7.88
2017	Mudflats	79 $\pm$ 21	16 $\pm$ 0.5	95 $\pm$ 20.5
2017	Sand beaches	124 $\pm$ 32	17 $\pm$ 5	141 $\pm$ 37
2017	Salt pan	81 $\pm$ 23.5	33 $\pm$ 15	114 $\pm$ 38.5
2017	Agricultural land	78 $\pm$ 8.21	13 $\pm$ 4.39	91 $\pm$ 9.88
2018	Mudflats	66 $\pm$ 24	13 $\pm$ 2	79 $\pm$ 22
2018	Sand beaches	117 $\pm$ 23	10 $\pm$ 9.5	127 $\pm$ 32.5
2018	Salt pan	96 $\pm$ 38	11 $\pm$ 2	107 $\pm$ 40
2018	Agricultural land	97 $\pm$ 10.76	14 $\pm$ 2.74	112 $\pm$ 13.09
2019	Mudflats	64 $\pm$ 7	13 $\pm$ 4	77 $\pm$ 11
2019	Sand beaches	103 $\pm$ 27.5	14 $\pm$ 6.5	116 $\pm$ 34
2019	Salt pan	82 $\pm$ 26	6 $\pm$ 4	88 $\pm$ 30
2019	Agricultural land	111 $\pm$ 13.06	18 $\pm$ 4.66	129 $\pm$ 15.46
2020	Mudflats	52 $\pm$ 7.5	4 $\pm$ 4	56 $\pm$ 11.5
2020	Sand beaches	88 $\pm$ 20	7 $\pm$ 2.5	95 $\pm$ 22.5
2020	Salt pan	56 $\pm$ 7	21 $\pm$ 17	77 $\pm$ 24
2020	Agricultural land	120 $\pm$ 16.58	27 $\pm$ 4.66	146 $\pm$ 19.23
2021	Mudflats	38 $\pm$ 4.5	9 $\pm$ 3	47 $\pm$ 7.5
2021	Sand beaches	54 $\pm$ 5.5	22 $\pm$ 5	76 $\pm$ 10.5
2021	Salt pan	46 $\pm$ 13	22 $\pm$ 9	68 $\pm$ 22
2021	Agricultural land	150 $\pm$ 17.82	17 $\pm$ 3.17	167 $\pm$ 20.78
2022	Mudflats	33 $\pm$ 1.5	10 $\pm$ 4.5	42 $\pm$ 6
2022	Sand beaches	45 $\pm$ 8	13 $\pm$ 1.5	58 $\pm$ 9.5
2022	Salt pan	35 $\pm$ 10	18 $\pm$ 5	53 $\pm$ 15
2022	Agricultural land	170 $\pm$ 19.99	22 $\pm$ 3.93	192 $\pm$ 22.86
2023	Mudflats	26	8 $\pm$ 3.5	34 $\pm$ 3.5
2023	Sand beaches	33 $\pm$ 2.5	10 $\pm$ 3	43 $\pm$ 5.5
2023	Salt pan	25 $\pm$ 7.5	14 $\pm$ 5	39 $\pm$ 12.5
2023	Agricultural land	185 $\pm$ 21.09	26 $\pm$ 4.47	211 $\pm$ 24.44

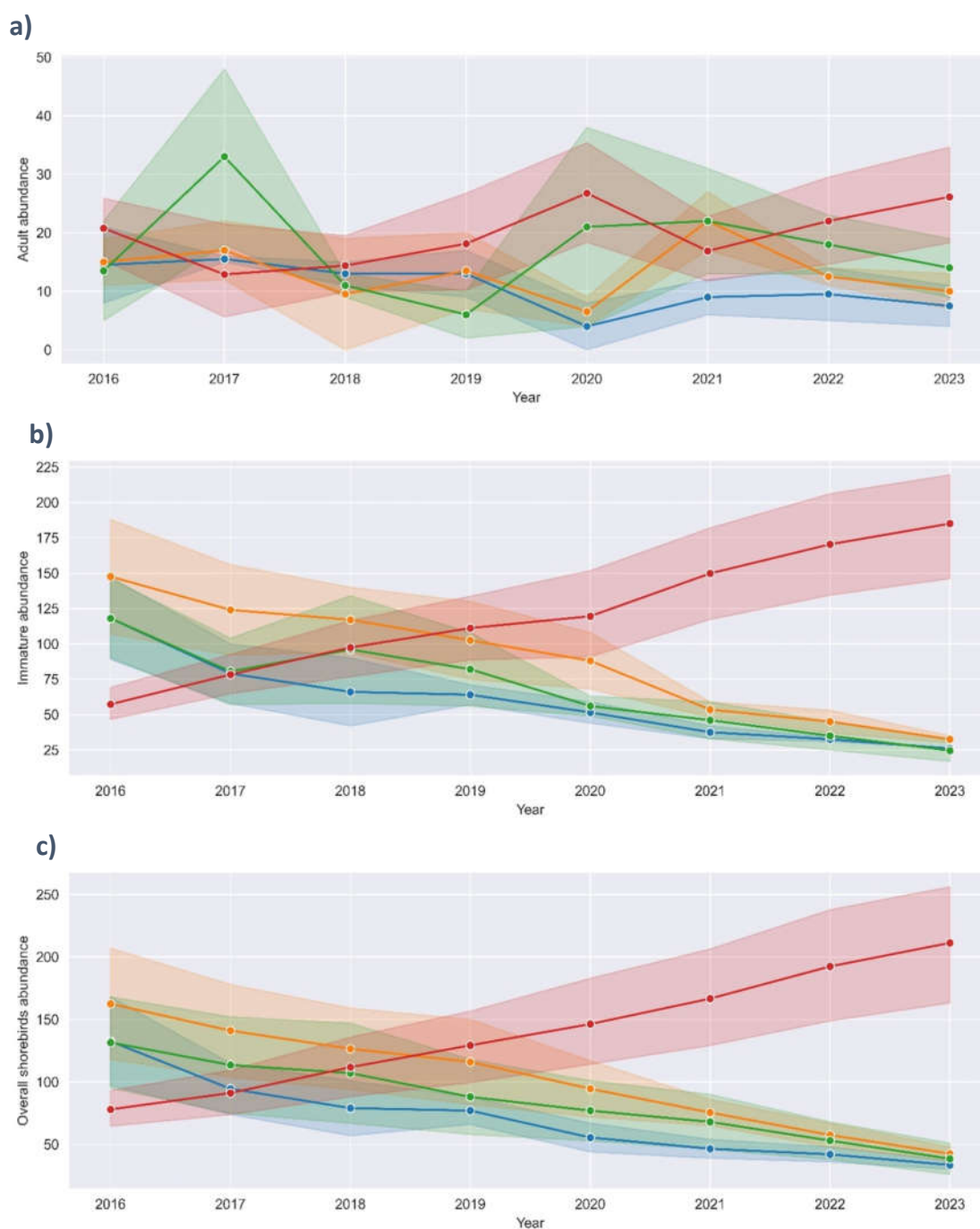


Figure 30. Temporal variation in shorebird abundance (mean $\pm$ SE) from 2016 to 2023, depicting; **(a)** adults, **(b)** immatures, and **(c)** overall abundance across mudflats, sand beaches, salt pan and agricultural land.

Table 16. Results of the generalized linear mixed model (GLMM) examinig the effects of year, habitat type and species (explanatory variables) on the abundance of overall shorebirds, adults and immatures (responses variables). Significant effects ($p < 0.001$) are highlighted.

Response variable	Explanatory variables	Level of effect	Parameter Estimate	SE	Df	F	P
Abundance of overall shorebirds ($R^2 = 0.41$)	Intercept		14.6606	0.532291	1	758.5862	0.0000
	Year	2016	-1.9390	1.021	7	3.627	0.0008
		2017	-2.5342	1.021			
		2018	-1.4390	1.021			
		2019	-0.5223	1.021			
		2020	-0.1890	1.021			
		2021	0.8705	1.021			
		2022	2.4301	1.021			
	Habitat type	Mudflats	-6.3894	1.036	3	47.722	0.0000
		Sand beaches	-2,3781	0.925			
		Salt pan	1.6786	1.018			
	Species	Tibetan Sand Plover	12.7096	1.083	12	24.016	0.0000
		Whimbrel	-1.3569	1.272			
		Greater Sand Plover	6.2056	1.272			
		Pacific Golden Plover	2.1459	1.770			
		Ruddy Turnstone	9.0024	1.272			
		Common Redshank	0.9634	1.129			
		Common Greenshank	0.7811	1.434			
		Black-tailed Godwit	-0.3836	1.429			
		Marsh Sandpiper	-3.9751	1.253			
		Common Sandpiper	-14.0711	1.429			
		Little Stint	0.6744	1.746			
		Grey Plover	-6.0711	1.951			
	Error				649		

Abundance of immature shorebirds	Intercept		12.3892	0.491	1	634.179	0.0000
(R² = 0.38)	Year	2016	-2.0744	0.9438	7	3.6088	0.0007
		2017	-2.4554	0.9438			
		2018	-0.7411	0.9438			
		2019	-0.1577	0.9438			
		2020	-0.6220	0.9438			
		2021	0.8661	0.9438			
		2022	2.2470	0.9438			
	Habitat type	Mudflats	-5.4848	0.9578	3	43.7293	0.0000
		Sand beaches	-1.5067	0.8558			
		Salt pan	0.6551	0.9417			
	Species	Tibetan Sand Plover	10.0026	1.0018	12	19.4730	0.0000
		Whimbrel	-0.9657	1.1759			
		Greater Sand Plover	5.4562	1.1759			
		Pacific Golden Plover	2.2163	1.6362			
		Ruddy Turnstone	8.0812	1.1759			
		Common Redshank	0.2418	1.0437			
		Common Greenshank	0.6388	1.3262			
		Black-tailed Godwit	0.7307	1.3209			
		Marsh Sandpiper	-3.2427	1.1583			
		Common Sandpiper	-11.7693	1.3209			
		Little Stint	0.7089	1.6138			
		Grey Plover	-5.3734	1.8034			
	Error				649		
Abundance of adult shorebirds	Intercept		2.27202	0.1509	1	226.4549	0.0000
(R² = 0.30)	Year	2016	0.13690	0.2896	7	1.4973	0.1651
		2017	-0.07738	0.2896			
		2018	-0.69643	0.2896			
		2019	-0.36310	0.2896			
		2020	0.43452	0.2896			

		2021	0.00595	0.2896			
		2022	0.18452	0.2896			
	Habitat type	Mudflats	-0.90558	0.2939	3	11.4632	0.0000
		Sand beaches	-0.86805	0.262642			
		Salt pan	1.02358	0.289003			
	Species	Tibetan Sand Plover	2.70738	0.307458	12	10.4335	0.0000
		Whimbrel	-0.39114	0.360898			
		Greater Sand Plover	0.74949	0.360898			
		Pacific Golden Plover	-0.06926	0.502149			
		Ruddy Turnstone	0.92136	0.360898			
		Common Redshank	0.69684	0.320302			
		Common Greenshank	0.14229	0.407000			
		Black-tailed Godwit	-1.11325	0.405379			
		Marsh Sandpiper	-0.71546	0.355490			
		Common Sandpiper	-2.30075	0.405379			
		Little Stint	-0.03384	0.495288			
		Grey Plover	-0.69658	0.553473			
	Error				649		

Considering overall shorebirds (adult and immature together) the monthly mean abundance varied significantly over species ($F = 24.01$; $df = 12$; $p < 0.001$) and between habitat types ($F = 47.72$; $df = 3$; $p < 0.001$), being highest in agroecosystems (140.82 ± 8.11), followed by sand beaches (102 ± 12.43), salt pan (84.56 ± 10.70) and mudflats (70.06 ± 9.14). Also, a significant difference was found over years ($F = 3.62$; $df = 7$; $p < 0.001$).

Equally, the same trend was shown by immature shorebirds with significant variation of their abundances recorded between species ($F = 19.47$; $df = 12$; $p < 0.001$) and habitats ($F = 43.73$; $df = 3$; $p < 0.001$) and over years ($F = 3.60$; $df = 7$;

$p < 0.001$) with the highest being in agroecosystems (121.04 ± 7.27) followed by sandbeach (88.75 ± 11.70), salt pan (67.25 ± 9.60) and mudflats (59.31 ± 8.29)

The abundance of adult shorebirds alone also varied significantly over species ($F = 10.43$; $df = 12$; $p < 0.001$) and habitat types ($F = 11.46$; $df = 3$; $p < 0.001$), whereas no significant variation observed over the years ($F = 1.49$; $df = 7$; $p = 0.16$) (Table 16; see also Table 17 for GLM results).

Table 17. General Linear Models showing a summary of models for measures of shorebirds abundance and their diversity (response variables).

Response variable	Explanatory variables	K	AIC	Δ AIC	Wi
Abundance of overall shorebirds	Year + Habitat type + Species	4	5768.777	0.000	0.999
	Habitat type + Species	3	5883.559	114.782	0.000
Abundance of adult shorebirds	Year + Habitat type + Species	4	3256.592	0.000	0.999
	Habitat type + Species	3	3273.116	16.524	0.000
Abundance of immature shorebirds	Year + Habitat type + Species	4	5741.932	0.000	0.999
	Habitat type + Species	3	5856.787	114.855	0.000
Diversity of shorebirds	Habitat type	2	213.840	0.000	0.987
	Year	2	222.777	8.937	0.011
	Year + Habitat type	3	227.815	13.974	0.000

Models are ranked according to Akaike's information criterion (AIC), the difference in AIC from the best supported model (Δ AIC), Akaike's weights (wi). For each species only the most parsimonious model (with highest k (number of parameters) is shown)

The diversity of shorebirds was found to be highest in agroecosystems (Shannon index: 2.52) and sand beaches (2.53) compared to salt pan (2.43) and mudflats (2.11). While agroecosystems, sand beaches and salt pan exhibited a stable yet fluctuating trend, an increasing diversity trend was observed in mudflats over the years, as depicted in Figure 31.

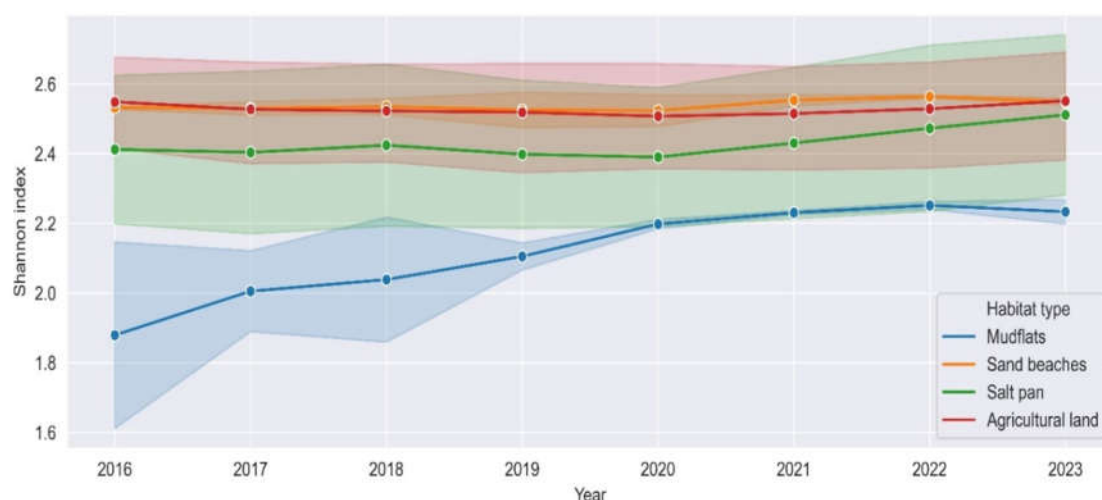


Figure 31. The trends of shorebird species diversity (Shannon index) across mudflats, sand beaches, salt pan and agricultural land habitats along the west coast of India from 2016-2023.

Discussion

Changes in environmental variables and its impacts on zooplankton communities

Habitat and seasonal influences on zooplankton abundance were recorded. Additionally, long-term, consistent declines in zooplankton were documented, with trends linked to temperature, salinity, pH, phosphates and phytoplankton abundance. Amphipod, chaetognatha, zoea, fish eggs, fish larvae, copepod, isopod and ostracods were the dominant groups of zooplankton in the samples (Raymont 1963; Harris et al. 2000; Boxshall & Halsey 2004; Goswami 2004).

A significant habitat and seasonal effect on zooplankton abundance was observed. Mangrove habitats had the highest abundance of zooplankton when compared to mudflats and sandy beaches. This is not surprising as mangroves accumulate nutrient-laden sediments from rivers that are periodically released into surrounding coastal waters (Santhikrishnan et al., 2021; Tarafdar et al., 2021) and thus promotes the growth of phytoplankton which in turn supports zooplankton growth. Sandy beaches, on the other hand, have lower niche diversity although they are still influenced by coastal mobilization of nutrients (Santhikrishnan et al., 2021; Tarafdar et al., 2021). The distribution of mudflats along the southwest coast of India is far more extensive compared to a scattered occurrence of mangroves

along river deltas (Nayak, 2005; Solanki et al., 2016). Thus, coastal abundance of phytoplankton and zooplankton is strongly influenced by the extent of mudflats and sandy beaches along the entire western shoreline.

The southwest monsoon is an important weather system that influences large portions of the Indian subcontinent and their coastal zones (Vinayachandran et al., 2004; Santhikrishnan et al., 2021). During the months of May to September, the region experiences heavy rainfall that causes freshwater from rivers to expand to the surrounding landscapes, causing release of nutrients and mobilization of salts. The resulting discharge of large volumes of water into coastal areas causes a reduction in the salinity at the deltas and alters upwelling patterns along entire shorelines (Santhikrishnan et al., 2021; Tarafdar et al., 2021). Thus, most coastal areas during the monsoons exhibit a change in phytoplankton communities, with an overall reduction in phytoplankton and zooplankton biomass (Vinayachandran et al., 2004; Rajkumar et al., 2009; Thillai et al., 2010; Santhikrishnan et al., 2021). Overall inorganic nitrogen declines during the monsoons due to lower incursion of neritic water, high influx of freshwater, along with an increase in turbidity, reduced light penetration generally resulting in a reduction in phytoplankton (Nandy & Mandal 2020; Santhikrishnan et al., 2021; Tarafdar et al., 2021). High Chl-a concentrations were recorded during winter and prior to the monsoons, while lower concentrations were recorded during the monsoon periods, consistent with regional phytoplankton abundance patterns (Nandy & Mandal 2020; Santhikrishnan et al., 2021). This pattern was mirrored by rising zooplankton abundance in winter and pre-monsoon patterns and declines in zooplankton after the monsoons, which has also been observed widely along Indian coastlines (Sahu et al., 2012; Nandy & Mandal 2020; Santhikrishnan et al., 2021). Despite clear seasonal and habitat related patterns in the abundance of phytoplankton and zooplankton, long-term patterns that are consistent with global environmental change were also evident.

Coastal environments around the world are undergoing long-term changes due to heavy input of nutrients from anthropogenic sources, due to increasing temperature and climatic anomalies resulting from global climate change (Kelly et al., 2021). As a result, entire coastal planktonic communities may be undergoing shifts (Kelly et al., 2021; McGowan et al., 2020; Tarafdar et al., 2021). Long-term declines in annual phytoplankton and zooplankton abundance were observed, in relation to globally and regionally shifting environmental variables. For example, the observed rise in water temperature is consistent with global increases in sea surface temperatures (SST) around the world's coastal and pelagic zones (Attrill, 2009; Amos et al., 2013). Increasing salinity in coastal areas and bays could be triggered by a variety of factors including freshwater extraction and consequent salt-water intrusion into inland regions (Akter et al., 2019; Senthilkumar et al., 2019). Additionally, oceanic acidification has been occurring worldwide due to high levels of atmospheric CO₂ uptake into marine environments (Gattuso et al., 2015). However, calcium carbonate mineral cycling could buffer the effects of acidification in shallow coastal areas and lagoons (Su et al., 2020). Global mapping of acidification hotspots indicate that the coastal areas of western India actually consist of carbonate poor shelves leading to more alkaline conditions (O'Mara & Dunne, 2020), which is consistent with the observed increase in alkalinity. The increasing phosphate levels across the study sites could be linked to high levels of phosphate and other deposits associated with reclamation efforts undertaken further inland along western India (Senthilkumar et al., 2019). In addition, direct discharge of phosphates from industries, household wastes and groundwater could enhance phosphate content of coastal zones (El Kateb et al., 2018; Vijayan et al., 2021). Thus, the long-term decline in zooplankton abundance appears to be associated with both large-scale factors (global sea surface temperature) and regional anthropogenic perturbations (salinization, rising phosphates and pH).

A consistently declining trend in nitrates was observed, except for an unusual increase in 2018, followed by severe flooding during south-west monsoon that

year. Declines in total inorganic nitrogen has been recorded in various coastal and shelf regions (Capuzzo et al., 2017; Schmidt et al., 2020) and this could trigger long-term changes in phytoplankton abundance (Schmidt et al., 2020; Santhikrishnan et al., 2021). Nitrogen and phosphorus are both intimately connected with phytoplankton abundance and community structure (Vajravelu et al., 2018; McGowan et al., 2020; Schmidt et al., 2020; Santhikrishnan et al., 2021). The influx of freshwater may inhibit upwelling of nutrients along the west coast of India, depending on the extent of the surface plume and its opposing effect on upwelling (Santhikrishnan et al., 2021). This, in turn, could affect nutrient content along the coastal areas, altering nitrogen-phosphorus ratios and their demand by phytoplankton, influencing acidification and ultimately abundance and community structure of phytoplankton (Su et al., 2018; Vajravelu et al., 2018; Opdal et al., 2019; McGowan et al., 2020; Santhikrishnan et al., 2021). Climate change predicts global reductions in oceanic phytoplankton productivity and there is mounting evidence to support this notion (Martinez et al., 2009; Le et al., 2019; Opdal et al., 2019). For example, a 'browning effect' due to increasing discharge of water carrying sediments (from rivers) could reduce light penetration in coastal euphotic zones, causing declines in phytoplankton in coastal areas in the North Pacific (Le et al., 2019) and the North Sea (Opdal et al., 2019).

Zooplankton around the world's coastal and pelagic oceans have also been declining (Lewandowska et al., 2014; Capuzzo et al., 2017; Schmidt et al., 2020). Mounting evidence indicates that warming influences nutrient availability to phytoplankton. In nutrient-limited waters, warming causes a rise in small phytoplankton (<20µm) (Lewandowska et al., 2014), including picocyanobacteria (0.2-2.0µm) (Schmidt et al., 2020). This causes a decline in overall phytoplankton biomass and a concomitant decline in zooplankton, due to lack of their preferred food, such as larger diatom species (Lewandowska et al., 2014). There has been a global rise in picocyanobacteria because of seasonal or long-term declines in nitrogen along with rising temperatures (Capuzzo et al., 2017; Schmidt et al., 2020).

Declines in phytoplankton associated with more localized processes such as acidification and reduced phosphates have also been recorded in Chilika Bay along the east coast of India (Tarafdar et al., 2021) or in the Sundarbans in the Bay of Bengal (Sarma et al., 2020). Furthermore, salinization of coastal waters could have effects on community structure of phytoplankton with increased salinity favoring more salinity-tolerant phytoplankton and zooplankton species (Nandy & Mandal., 2020; Rajkumar et al., 2020). Thus, long-term declines observed in phytoplankton productivity in this study are consistent with environmental degradation arising from anthropogenic nutrient influx, coastal salinization, and warming temperatures. (Lewandowska et al., 2014; Capuzzo et al., 2017; Schmidt et al., 2020).

Widespread occurrence of foot trembling behaviour

In the current investigation, all seven species of shorebirds under observation with diverse mode of foraging techniques demonstrated foot trembling behaviour in both mudflats and mangroves within the KVCR. This observation challenges the conventional understanding that foot trembling is exclusively a behavioural adaptation among visual foraging shorebirds. The revelation that foot trembling is also displayed by strictly tactile foragers and opportunistically visual/tactile foragers underscores the broad occurrence of this behaviour across shorebird species. This phenomenon occurs regardless of their morphological or behavioural characteristics, but is closely linked to habitat conditions that affect prey availability. In recent years, there has been a notable increase in the frequency of foot trembling behaviour among visual foraging shorebirds, in mudflats, such as Greater Sand Plover and Pacific Golden Plover. Until 2018, a similar trend was observed among Tibetan Sand Plovers as well. Foot trembling is recognized as a mechanism to enhance prey detectability employed by these shorebirds (Cestari, 2009) (Figure 32). The rising prevalence of foot trembling suggests a potential decrease in prey detectability within these habitats, possibly attributable to declining prey abundance and diminished surface activity of prey items. Li et al. (2020) have suggested that alterations in habitat conditions may underlie these trends,

impacting prey availability and rendering them less detectable to foraging shorebirds.

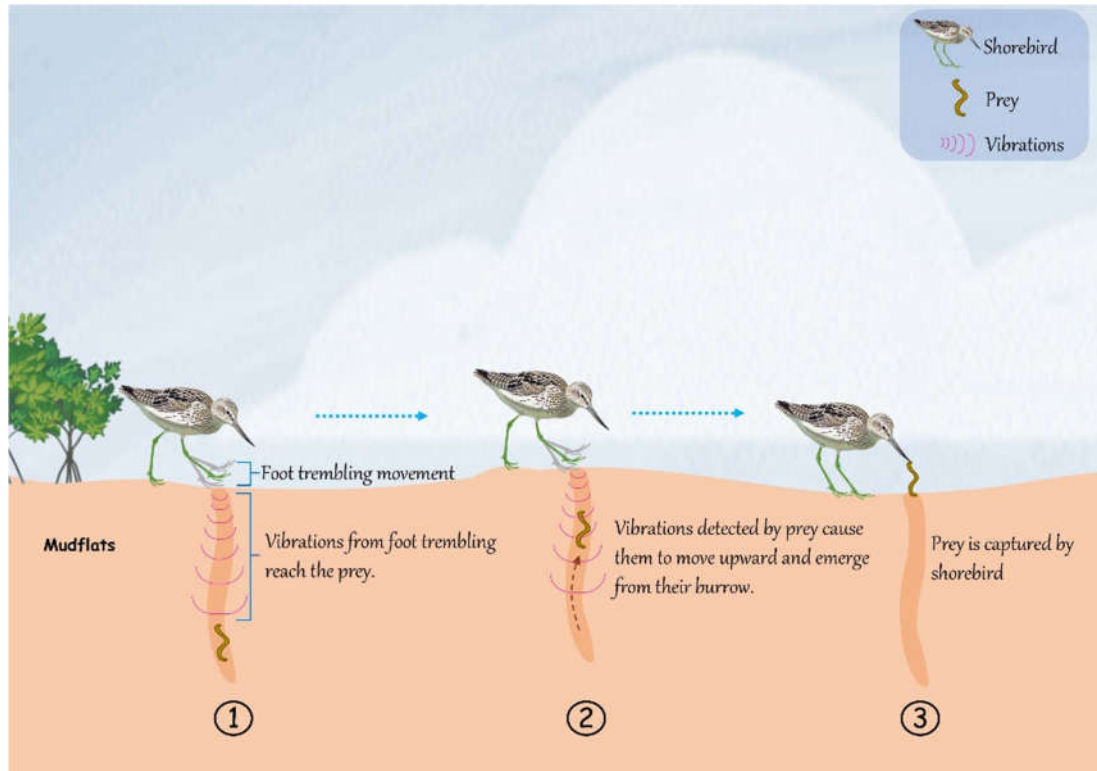


Figure 32. The graphical illustration depicts shorebirds utilizing foot trembling behaviour to facilitate the capture of buried prey.

Aarif et al. (2021a) highlighted the severe depletion of invertebrate prey at KVCR, linked to various environmental adversities including rising air and water temperatures. Sediment hardening at KVCR was also observed as affecting polychaete abundance (Musale & Desai, 2011). This depletion, compounded by temperature increases, particularly affects burrowing species such as crabs and polychaetes, reducing their surface activity. Changes in sediment texture, including increased sand deposition, contribute to the accelerated heating of mudflat surfaces, further diminishing invertebrate emergence and activity. Thermal stress on intertidal organisms leads to decreased metabolic rates and activity, with benthic organisms seeking refuge in deeper layers or burrows to mitigate thermal stress (Esser et al., 2008). Further, shorebirds, primarily guided by vision, face increased vulnerability in open habitats due to their wider blind area above their

heads (Martin & Piersma, 2009). During foot trembling, these shorebirds adopt a posture with elevated heads while tapping their feet on the ground facilitating the capture of deeply buried prey items and the posture potentially provides enhanced predator visibility to the shorebirds.

In contrast to their behaviour observed on mudflats, the Greater Sand Plover and Pacific Golden Plover exhibited a relatively low frequency of foot trembling activity within mangrove habitats, with occasional notable increases during certain years. Similarly, the Tibetan Sand Plover demonstrated a comparable trend until the year 2018. This deviation in behaviour could potentially be attributed to the higher abundance of macrobenthic invertebrates in vegetated habitats than in non-vegetated ones. The macrobenthic invertebrates tend to seek out microhabitats with favorable conditions during periods of thermal stress (Vianna et al., 2020). Additionally, during the hottest hours of the day, invertebrate activity tends to be higher in vegetated habitats compared to areas lacking vegetation (Vianna et al., 2020). This could potentially enhance the foraging success of visual predator shorebirds in vegetated mangrove habitats without the aid of foot trembling.

The notable and most concerning discovery in the current investigation is the heightened dependence of tactile forager shorebirds on foot trembling behaviour within both habitats of KVCR. Tactile foragers possess the unique ability to sense prey buried in sediment through remote touch, detecting mechanical vibrations in the substrate (du Toit et al., 2024). However, environmental changes can interfere with this behaviour. Vegetation cover, for instance, impedes the pressure fields of buried prey (de Fouw et al., 2016), while substrate water content significantly influences prey detection, with wetter sediments facilitating better vibration transmission (du Toit et al., 2024). The KVCR habitats are currently experiencing uncontrolled mangrove proliferation and expansion onto mudflats, exacerbating habitat alterations (Aarif & Prasad, 2014). Changes in sediment texture, notably decreasing clay and increasing silt content due to sand deposition (Rubeena et al., 2023), diminish water retention capacity, hastening habitat drying during low tide.

Consequently, despite the presence of prey, poor vibration transmission in the soil renders it undetectable to tactile foraging birds, prompting reliance on surface-level prey capture mechanisms (du Toit et al., 2024). The increased frequency of foot trembling behaviour among tactile shorebirds points to the decreased prey availability or detectability which in turn indicates significant habitat degradation, profoundly impacting prey availability for species with intricate evolutionary adaptations.

Opportunistic shorebirds employ a range of foraging strategies influenced by factors such as beak morphology, prey type, and substrate composition (Angarita-Báez & Carlos, 2023b). Unlike tactile foragers, these adaptable species do not exhibit consistent spatial patterns in foot trembling behaviour. In order to fully comprehend these varied behaviours of these larger, shorebird species requires in-depth investigations, including analyses of prey types and capture success rates facilitated by foot trembling. The utilization of foot trembling by even highly adaptable shorebirds in these habitats emphasizes a notable decline in prey availability and detectability, leading to reduced energy intake. Moreover, recent studies have shown that this already limited prey is further contaminated with heavy metals and microplastics, which infiltrate the food web (Aarif et al., 2023, 2025; Athira et al., 2024a, 2024b, 2025). These combined factors, further reduces shorebird fitness and contributes to population declines. These findings highlight the urgent need for immediate conservation measures to address these multiple challenges within the habitat.

Diverse prey transport mechanisms

This study documented three distinct prey transport mechanisms among shorebirds in the degraded KVCR mudflats: surface tension transport, water-dependent inertial transport, and distal rhynchokinesis. These mechanisms varied with species morphology, demonstrating functional adaptations to environmental constraints. Despite habitat degradation and reduced prey availability, shorebirds exhibited

notable plasticity in foraging strategies, enabling effective prey capture and handling under suboptimal conditions.

The study observed that medium-sized, straight-billed shorebirds, such as the Common Greenshank and Common Redshank, employ a surface tension-based prey transport mechanism to consume microscopic prey suspended in the water column. This mechanism, characterized by rapid tweezing like beak movements, enables efficient and quick ingestion of prey while minimizing energy expenditure (Rubega & Obst, 1993; Estrella et al., 2007a). Although these species typically rely on pecking and probing to capture benthic macroinvertebrate prey, they may be shifting their foraging strategies in response to intensified interspecific competitions and declining prey abundance and availability at KVCR (Aarif et al., 2021a). To cope with this pressure, shorebirds may be increasingly exploiting pelagic prey, a strategy facilitated by their elongated bills, which allow for alternative foraging techniques in water column (Aarif et al., 2024).

Changes in the substrate composition further influenced prey availability and foraging efficiency. Structural alterations, such as sand deposition, have modified sediment texture in KVCR mudflats (Aarif & Musammilu, 2018; Rubeena et al., 2023). The reduction in clay content has resulted in hardened and less penetrable sediments limiting bill-probing efficiency and reducing prey capture rates (Myers et al., 1980; Milsom et al., 2002). Additionally, rising air and water temperatures may drive burrowing invertebrates into deeper substrate layers, further restricting access to benthic prey. These environmental constraints have extended the foraging time required to meet energetic demands at KVCR, compared to adjacent, less-degraded habitats.

Similarly, Grey Plovers, which generally rely on visual foraging, were observed employing a water-dependent inertial transport mechanism, particularly during high tides. Feeding during high tide is considered an opportunistic foraging behaviour among shorebirds and is often adopted when low tide foraging is insufficient to meet the high energy demands of long-distance migration (Masero,

2002). This mechanism involves rapid, controlled water intake and tweezing beak movements to handle small but visible prey. The use of water as both a transport medium and a lubricant highlights behavioural plasticity that enhances foraging efficiency. Similar behaviour has been reported previously (Prakash et al., 2008) and is particularly effective for prey too large for surface tension-based prey transport yet unsuitable for direct ingestion.

Larger nereidid polychaetes were identified as key prey items for Grey Plovers and Pacific Golden Plovers (Iwamatsu et al., 2007; Kato et al., 2000). However, sediment hardening at KVCRC has negatively impacted polychaete abundance and surface emergence (Musale & Desai, 2011). A recent increase in foot trembling behaviour among larger plovers in KVCRC suggests reduced prey detectability (Athira et al., 2025), further supporting the impact of sediment alterations on prey accessibility. Consequently, inertial transport may serve as an adaptive foraging strategy for Grey Plovers to enhance energy intake under degraded conditions. This strategy may also help reduce competition with larger shorebirds such as Bar-tailed Godwits, which primarily target polychaetes at KVCRC (Athira et al., 2024c).

Larger shorebirds, such as Bar-tailed Godwits and Whimbrels, are primarily tactile foragers but can shift to visual foraging when beneficial (Finn et al., 2007). Tactile foraging relies on mechanoreceptors in the bill tip to detect prey through pressure and vibration cues (van de Kam et al., 2004). These species typically target larger, deep-burrowing benthic invertebrates to meet their high energy demands (Duijns et al., 2009). In this study, they were observed foraging on dry mudflats using pecking and probing, facilitated by distal rhynchokinesis—a mechanism in which the distal part of the upper jaw flexes independently to secure and transport large invertebrate prey. This finding builds on earlier research, suggesting that distal rhynchokinesis enhances prey-handling efficiency by reducing intra-oral transport time. Unlike medium-sized shorebirds that optimize feeding for small-prey profitability, larger shorebirds require high-energy prey. Their elongated bills, combined with rhynchokinesis, provide an adaptive advantage by facilitating rapid prey processing in energetically demanding environments.

The coexistence of diverse prey transport mechanisms within a single degraded habitat highlights the behavioural and morphological plasticity of shorebirds. As habitat loss, pollution, and declining prey abundance continue to reshape foraging landscapes, the ability to switch between surface tension transport, inertial transport, and distal rhynchokinesis may enable shorebirds to cope with environmental variability and sustain energy intake under changing ecological conditions.

Transition of habitats-oversummering shorebird recruitment to agroecosystems

The current research found that there has been a significant decrease in the abundance of migrant shorebirds that are over-summering in the coastal regions of India (Figure 30). This is likely a reflection of the prevailing pattern observed in prior investigations, that have cautiously outlined the enormous downturn in wintering shorebird populations along the west coast of India (Aarif & Musammilu, 2018). This decline is attributed to the alterations in environmental factors encompassing changes in rainfall patterns (Aarif et al., 2021a), variations in hydrological & substrate qualities (Rubeena et al., 2023), reduction in primary productivity (Athira et al., 2021) & macrobenthic prey availability (Aarif et al., 2021a), and the biomagnification of heavy metals (Aarif et al., 2023) and microplastics (Athira et al., 2024a). These factors collectively contributed to changes in the migratory schedules of shorebirds (Aarif et al., 2021a) and can potentially induce diversity shifts among them (Shamna et al., 2023; Rashiba et al., 2023). The phenomenon of conspicuous decrease in over-summering population of shorebirds in KVCR and adjacent sand beaches is primarily observed to be driven by a substantial decrease in the number of juvenile shorebirds over the years (Table 15), contrasting the stability observed among the adult population. Interestingly, in adjacent agricultural areas, there is a significant rise in both the total abundance of shorebirds and the count of immature individuals, while the adult shorebird population remains consistently steady. These results are consistent with very recent investigation (Byju et al., 2024), demonstrating a significant alteration in the wintering habitats of shorebirds along the east and west coasts of India. The study observed the transition from intertidal mudflats to sand beaches and subsequently to agroecosystems and it

underscores the profound consequences of severe habitat degradation. These transitions, which was initially thought to be mere adaptive strategies of observed population of shorebirds, have now proven to hold deeper insights, as revealed by the present study. The stability observed in adult shorebird populations in both the habitats can be attributed to the exceptional fidelity exhibited by shorebirds to their wintering sites (Leyrer et al., 2006; Gill et al., 2014; Verhoeven et al., 2020). In addition to their abundance, the diversity of over-summering shorebirds was highest and showed a relatively stable trend over the years in agro-ecosystems (Figure 31). However, the increasing diversity trend observed in mudflats does not indicate a positive pattern, as the abundance of shorebirds significantly declined over the years in all coastal habitats.

Tavera et al. (2020) found that juveniles refraining from migration exhibited greater survival rates compared to those migrating back to the breeding grounds in their first year of life. Stopover sites and wintering locations can be viewed as specific intervals along the flyway where shorebirds slow down, experiencing reduced flight speeds, heightened predation risks, and distinct per-capita mortality parameters and greater vulnerability for younger shorebirds (Gourley & Liu, 2015). Therefore, the decisions made by juvenile shorebirds regarding their wintering locations have a substantial impact on their overall fitness (Senner et al., 2015). Earlier assessments indicated that, Kadalundi-Vallikkunnu Community Reserve mudflats and the adjoining sand beaches provided high-quality foraging grounds for wintering and over-summering shorebirds, aiding in their preparation for migration and breeding. However, the most recent scientific reports indicate a substantial decline in the quality of these coastal habitats essential for these migratory shorebirds. Over-summering would only be favoured by natural selection if survival of over-summering individuals was raised sufficiently to compensate for the missed breeding opportunity (Wille & Klaassen, 2022).

In addition, shorebirds were demonstrated as exhibiting a high degree of behavioural flexibility in response to variable environmental conditions (McGuire et al., 2020). The pivotal role of juvenile shorebird survival is evident, significantly influencing the insights into population of long-distance migrants. The loss of

refueling habitats has the potential not only to alter the composition of traits in the current population but also to have evolutionary consequences (Gill et al., 2014; Tarka et al., 2015). Therefore, the hypothesis is proposed that the growing presence of over-summering juveniles in agroecosystems, coupled with the decline in degraded coastal habitats, could represent an ongoing evolutionary adjustment driven by natural selection. However, further long-term studies over multiple generations are imperative to validate this hypothesis comprehensively.

The migration timing in shorebirds frequently varies among age groups, as adults tend to migrate several weeks ahead of juveniles (Alerstam, 1990). The enduring loss and degradation of habitats in the coastal regions of India result in food scarcity at refueling sites. In this context, mature individuals that arrive early gain advantages, accessing less-depleted food sources and having abundant time for refueling or exploring alternative sites, setting them apart from their immature counterparts arriving later. Furthermore, mature individuals with substantial fuel reserves are better equipped to endure unfavorable conditions than juveniles with limited fuel stores (Krkošek et al., 2007). Additionally, the diminished carrying capacity of habitats poses challenges for inexperienced juvenile shorebirds, hindering their ability to meet daily energy requirements, cope with competition and predation pressure (Tavera et al., 2020). It has been suggested that the unequal mortality among birds differing in migration timing and fuel reserves can drive natural selection against latecomers and individuals with smaller fuel stores, potentially shaping the composition of migration phenotypes at stopover sites as lesser fit individuals are selectively eliminated.

It has long been hypothesized that over-summering phase provides a survival advantage over migration (Tavera et al., 2020). Therefore, over-summering shorebirds must accumulate sufficient resources, storing them as triglycerides in adipose tissue. This is crucial because migratory movements primarily rely on the oxidation of fatty acids (FA), which are transported to muscles through the circulatory system. Migrants are facing severe and rapid challenges regarding access to their traditional food sources, were observed as increasingly using anthropogenic habitats with

associated changes in their diet. Araújo et al. (2019), observed that the Black-tailed Godwit, known for its extensive migratory journeys, has undergone a significant dietary transformation in recent decades. While previously reliant on an animal-based diet, these birds now primarily consume rice seeds during their non-breeding period. This shift appears to enhance their migratory fuel stores, achieved through a notable surge in *de novo* lipogenesis (DNL) activity. This is significant since the propensity is notably pervasive among larger shorebird species, where juvenile individuals emerge as a nearly ubiquitous phenomenon. Therefore, only a limited number of immature individuals opt for over-summering in coastal habitats, suggesting a persistent variation in nutritional preferences within the same population likely driven by selective pressures.

It is well established that juvenile shorebirds tend to have higher parasite prevalence and lower specific immunity to parasites compared to conspecific adults. It has been suggested that, the migration allopatry between juveniles and adults may reduce the chance of adults infecting juveniles with the parasites they are carrying (Krkošek et al., 2007; Strathmann et al., 2002). Along with that, immature individuals are expected to prioritize sexual maturation over immune function (Lozano & Lank 2003; Noreen et al., 2011). Immunity acts as a focal point influenced by various environmental stressors. Significant levels of toxic pollutants such as heavy metals (Aarif et al., 2023) and microplastics (Athira et al., 2024a) and their trophic transfer along the food chain, reaching shorebirds have been identified in the coastal habitats along the west coast of India. These findings suggest that these pollutants may be driving habitat shifts among immature shorebirds, possibly as a strategy to avoid parasitic infections and reduced fitness. Parasite infections are also expected to impact foraging decisions in migratory birds, favouring dietary antioxidants although fattening is a priority (Mancio-Silva et al., 2017; Zuzarte-Luís et al., 2017).

Therefore, this study identifies a gradual shift within the young shorebird population of the west coast of India, as they are steadily recruited into

agroecosystems, departing from their conventional coastal habitats. This phenomenon demands detailed, long-term research to ascertain whether this shift is evolutionarily favorable or will catapult them further toward extinction. Because juvenile shorebirds are assumed to be naive about finding suitable habitats or avoiding dangerous sites.

Overall, this chapter aims to bridge existing knowledge gaps in understanding the influence of environmental changes on zooplankton abundance and shorebird habitat utilization and foraging strategies. Understanding these responses is crucial for developing effective conservation strategies in rapidly changing coastal ecosystems.



The impact of long-term environmental change on zooplankton along the southwestern coast of India

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Abstract Environmental pollution and climate change are causing major changes in the marine environment. Coastal zones around the world are experiencing changes such as nutrient influx, resulting in altered plankton communities. The aim of this study was to determine the response of zooplankton to the changes in the environmental variables in the coastal zone of the Arabian Sea, Southwest Coast of India, over 10 years. Zooplankton abundance, chlorophyll-a concentrations, and water

quality variables (rainfall, nitrates, phosphates, pH, water temperature, and salinity) were quantified from January 2010 to December 2019. Water temperature, pH, salinity, and phosphates increased steadily across the sites during the study period whereas chlorophyll-a and nitrates decreased. Rainfall abundance was not exhibiting any patterns or trends. The effects of the sampled environmental variables on zooplankton abundance were tested using generalized linear mixed models. Salinity and phosphates negatively affected the zooplankton abundance whereas water temperature, pH, and chlorophyll-a concentration

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Widespread Occurrence of Foot Trembling Behaviour Among Wintering Shorebirds in a Degraded Coastal Ecosystem

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Abstract

This study examines foot trembling behaviour in shorebirds at an important wintering ground along the west coast of India, challenging the traditional notion that this behaviour is limited to visual foragers. The research was carried out in two primary habitats within the Kadalundi-Vallikunnu Community Reserve: mudflats and mangroves. The investigation focused on seven migratory shorebird species, including visual foragers (Tibetan Sand Plover, Greater Sand Plover, and Pacific Golden Plover), tactile foragers (Sanderling and Terek Sandpiper), and opportunistic foragers (Common Redshank and Common Green-shank). Shorebird monitoring was conducted during low tide using direct visual counts and video recording. The findings demonstrate that foot trembling is prevalent across all species studied, regardless of their foraging strategy, and is closely linked to habitat conditions affecting prey availability. Moreover, the study indicates that tactile foragers are particularly reliant on foot trembling, suggesting significant habitat degradation that impacts prey availability for species with specialized evolutionary adaptations.

Significance Statement

The study investigates the widespread occurrence of foot trembling behaviour among migratory shorebirds at an important wintering ground along the west coast of India. By examining this behaviour across species employing various foraging strategies, the research aims to determine whether foot trembling is an adaptive response to habitat degradation.

Keywords Foraging behaviour · Foot trembling · Prey detectability · Sediment hardening · Thermal stress

Introduction

Long-distance migratory shorebirds, whose populations are declining worldwide [1, 2], depends on intertidal habitats during the non-breeding seasons [3]. During this period, foraging behaviour is crucial for shorebirds, as it ensures their survival and successful migration to breeding grounds [4]. Shorebirds use diversified habitats as stop-over and wintering sites to replenish their energy and nutrient reserves [5]. The tidal cycles at these habitats fundamentally influence the spatio-temporal distribution of foraging territories, with foraging activity mainly restricted to low tide [6]. Consequently, due to the limited availability of foraging habitats both temporally and spatially, shorebirds develop various morphological, evolutionary, and behavioural adaptations to enhance foraging efficiency [7].

The foraging ecology of shorebirds is often characterized by food selection, habitat preference, and prey capturing tactics or behaviour employed by them in a particular habitat [8, 9]. The morphology of a bird is considered an important factor in restricting the range of foraging techniques it can perform [10]. The bill length and leg length influence the preference for foraging water depths by shorebirds [11]. Benthic macroinvertebrates (e.g., polychaetes, bivalves, and crustaceans) serve as critical, nutrient-rich prey for migratory shorebird species at coastal or intertidal,

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Over-Summering Shorebird Recruitment to Unconventional Habitats on the West Coast of India

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Abstract

The rapid decline of migratory shorebirds in coastal habitats along the west coast of India and their recent shift toward agroecosystems as wintering grounds, raises concerns about adaptive habitat switching. This study investigated 13 common migrant shorebird species during their over-summering period (June–July) from 2016 to 2023, focusing on age-based demographic patterns across coastal and agroecosystems. The analysis revealed a significant decline in both the overall abundance of over-summering shorebirds and the proportion of immature individuals within the coastal ecosystem. In contrast, agroecosystems experienced a significant increase in both total abundance and the presence of immature shorebirds. Adult shorebirds exhibited consistent patterns across both habitat types, suggesting strong site fidelity. While these findings imply habitat degradation as a primary driver of the observed shift, further research spanning multiple generations is necessary to fully comprehend the underlying factors and the potential for ongoing evolutionary adjustments within the shorebird population. Additionally, the study underscores the urgent need for both coastal habitat restoration and the protection of agroecosystems, recognizing their crucial role as nursery grounds for the immature shorebird population along the west coast of India.

Keywords Rice field · Evolutionary adjustment · Habitat switching · Young shorebirds · Over-summering

Introduction

Over-summering is a phenomenon observed in migratory bird populations, where certain individuals forgo migration [1]. During this extraordinary occurrence, young birds, occasionally accompanied by solitary adults, elect to remain in non-breeding grounds while the bulk of the population migrate back to their breeding grounds. The phenomenon has been documented across 15 different bird families, with a notable prevalence among shorebirds [2]. Over-summering shorebird populations may also include adults in poor condition, unable to meet the energetic demands and risks of migration [3]. Although, one-year-old shorebirds exhibit an elevated tendency for over-summering across various documented species [4]. Understanding the spatiotemporal dynamics of over-summering shorebird populations is crucial to directing extensive conservation efforts towards these migratory species.

The Indian subcontinent is a key wintering ground for shorebirds migrating along the Central Asian and South Asian Flyways [5–7]. Previous studies have documented the presence of over-summering shorebirds along India's

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CHAPTER 3

ENVIRONMENTAL POLLUTION AND TROPHIC TRANSFER TO SHOREBIRDS ACROSS COASTAL ECOSYSTEMS

Introduction

Environmental pollution is an indication of contamination of the earth's living and non-living components in a way and to a degree that is harmful to the typical, ideal environmental processes (Suzuki et al., 2020). Pollutants yield primary and secondary damages, with primary damage quantified and monitored, while secondary damage disrupts the delicate balance of the biological food web and can be noticed only over prolonged durations (Yadav et al., 2022). In global scenario the coastal pollution rates are twice than that of inland sites (Santhaseelan et al., 2021). Heavy metals and microplastics are two of the most concerning environmental pollutants today due to their potential to cause harmful effects on ecosystems and human health.

Studies on sentinel species provide an interpretation of pollution levels and a comprehensive measurement of all its impact on the ecosystem. Shorebirds exhibit crucial traits of sentinel species, such as clear responses to environmental variability, playing crucial roles in shaping coastal food webs, and indicating anthropogenic impacts on ecosystems (Hazen et al., 2019). Long-distance migrant shorebirds are the most rapidly declining group of birds around the globe (Aarif et al., 2014, 2020, 2021a) which rely on habitats and resources along their entire migratory route. Anthropogenic mediated changes such as climate change and loss or modification of their wintering and stopover grounds were regarded as well-recognized causes of their population declines. Being the top-level predators in coastal ecosystem, they are highly vulnerable to environmental pollution owing to their unique migratory ecology and foraging behaviour (Aarif et al., 2023). However, limited research has examined pollutant accumulation in shorebirds, particularly in relation to microplastics and heavy metals. This study addresses these knowledge gaps by assessing pollutant accumulation in shorebirds and their associated ecosystems along the west coast of India.

Historical review

The proximity of intertidal zones to urban centres with dense human populations is associated with increasing plastic pollution. Rivers serve as major conduits for plastic waste, channelling debris from surface runoff and sewage effluents into these coastal areas (Sutkar et al., 2023). Microplastics are commonly referred to plastic particles with a size smaller than 5 mm. They can be formed by the disintegration of larger plastics (Law & Thompson, 2014) or that are manufactured by industrialists for use in cosmetics or personal care products (Crawford & Quinn, 2017). Microplastic contamination has been identified as a global issue but its mechanisms of action in triggering troubles in ecosystem structure and function have not yet been completely unravelled.

In aquatic environments, microplastics transform due to additive leaching, biofouling, and blend with aggregates. These changes alter their buoyancy, causing them to settle in benthic ecosystems (Wang et al., 2016). This deposition poses significant risk to lower trophic-level organisms, such as plankton, which are highly susceptible to microplastic ingestion (Rodrigues et al., 2021). Importantly, this ingestion initiates trophic transfer and subsequent biomagnification within the food web, posing a potentially greater threat to aquatic organisms than macroplastic debris (Gao & Zhang, 2024). Therefore, coastal zones accumulate microplastics along with nutrients, becoming potential hotspots for interactions between biota and plastics. Intertidal regions serve as important nurseries and foraging grounds for species across multiple trophic levels including a wide range of macrobenthos, fishes, and shorebirds (McFadden et al., 2016; Athira et al., 2024a). Some smaller shorebirds exhibit a unique feeding strategy by directly consuming biofilms—complex structures comprising cells, sediments, and extracellular polymeric substances produced by microphytobenthos (Kuwae et al., 2008). Additionally, medium-sized shorebirds directly consume plankton, utilizing surface tension transport mechanisms (Prakash et al., 2008). Consequently, any pollutants including microplastics in coastal water, sediment, or biofilms, or those ingested by

organisms at any trophic level, can ultimately reach shorebirds, many of which are apex predators (Aarif et al., 2023; Athira et al., 2024a).

Heavy metal pollution is also concerning due to their toxicity, intrinsic persistence, non-biodegradable nature, and accumulative behaviours (Ali et al., 2019). Significant quantities of heavy metals from anthropogenic activities are discharged into rivers, which can be strongly accumulated and biomagnified along water, sediment, and aquatic food chain (Ahmed et al., 2019). Their effects on coastal environments and organisms can be substantial, in spite of restoration efforts (Mok et al., 2023). Shorebirds occupy upper trophic levels and are therefore vulnerable to heavy metal pollution (Aarif et al., 2023). The physiological impacts of heavy metal accumulation in shorebirds vary with feeding habits, growth, age, reproductive stage, moulting, migration and distribution (Pandiyan et al., 2020). The impacts of heavy metal bioaccumulation on species-specific physiological, ecological, and evolutionary processes require further exploration (Aarif et al., 2023).

Several studies have documented the presence of microplastics in shorebirds across the globe. For example, Lourenço et al. (2017) reported microplastics in sediment, macroinvertebrates, and two species of resident shorebirds in Europe and West Africa. Rossi et al. (2019) documented microplastic ingestion in American Oystercatchers (*Haematopus palliatus*) along Brazil's coast. Ward et al. (2022) explored the potential transfer of microplastics from horseshoe crab eggs (*Limulus polyphemus*) to shorebirds in New York. Recently, Liu et al. (2023) identified microplastics in different tissues of smaller shorebird species along the Yellow Sea coast of China and highlighted a possible link with foraging strategies. However, beyond the visual/tactile foraging tactics, shorebirds exhibit diversified food acquisition behaviours, depending upon their morphology (Baguette et al., 2023). There are no comprehensive studies documenting the occurrence and characterisation of microplastics in wintering shorebirds with different food acquisition behaviours as well as their potential routes to shorebirds from

environmental sources through prey items at various trophic levels. There is a knowledge gap in the comprehensive understanding of the abundance of microplastics in a spatio-temporal scale and its association with the prey and shorebird abundance in these ecosystems, which is imperative for developing effective conservation strategies.

With the exception of Pandiyan et al. (2020) from the east coast and Aarif et al. (2023) from the west coast on estimating heavy metal accumulations, studies on their bioaccumulation in shorebirds are very limited from CAF. Also, no studies were undertaken from the Indian scenario on understanding the occurrence or microplastic accumulations in shorebirds community. Also, the potential effects of anthropogenic pollutants have not yet been discussed. Knowledge gaps exist regarding the effects of heavy metals on shorebird populations and the potential for synergistic effects with other environmental stressors. Recent studies confirmed that the heavy metals have high affinity to adsorb on to microplastics (Liu et al., 2022). The existence of this cocktail of pollutants is more dangerous, which could lead to undesirable synergistic consequences.

Results

Occurrence of microplastics in environmental samples and shorebirds

The present study observed the occurrence of microplastics in all the water (Figure 33a), sediment (Figure 33b), benthic macroinvertebrate prey (Figure 34) and droppings samples of shorebirds (Figure 35), collected from the selected study sites.

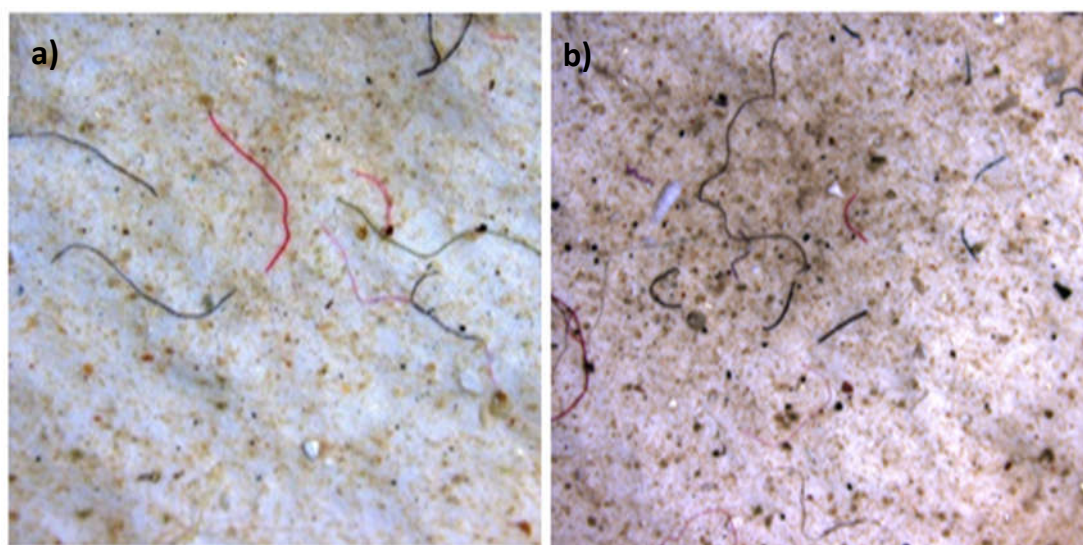


Figure 33. (a) Microplastics in water samples from KVCR mudflats and (b) microplastics in sediment samples from KVCR mudflats.

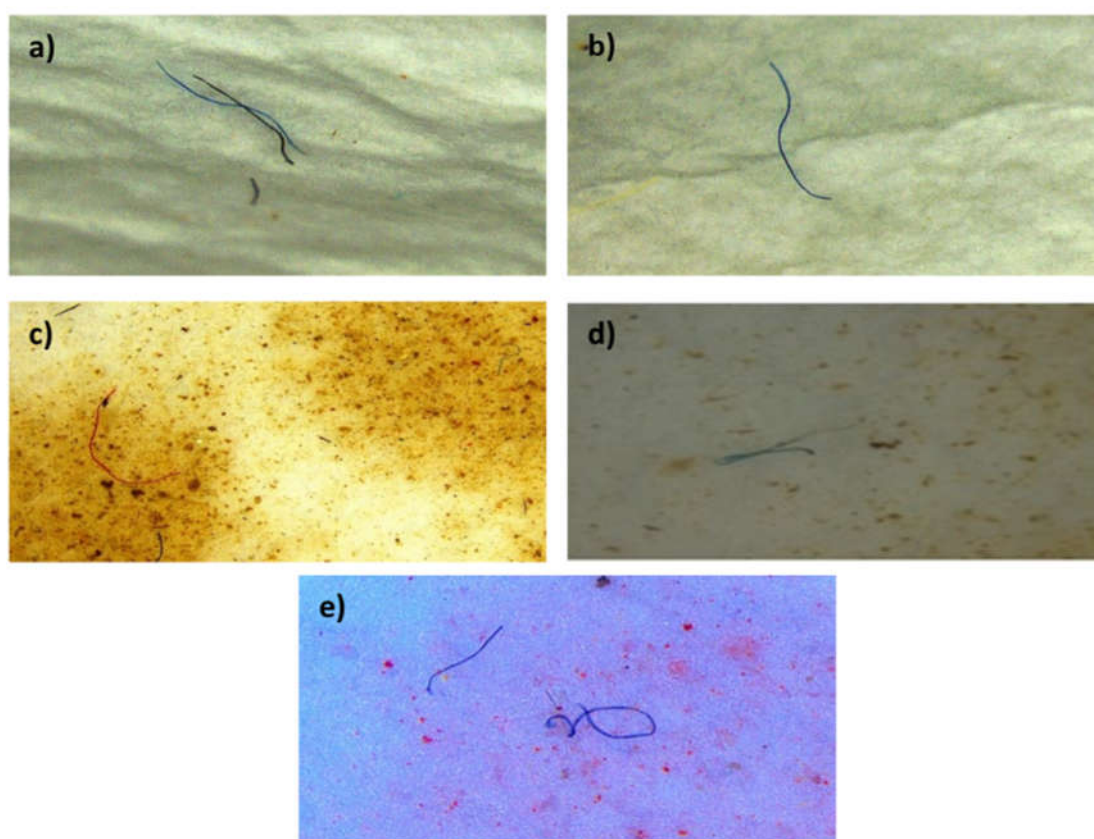


Figure 34. Microplastics observed in benthic macroinvertebrates under stereozoom microscope; (a) *Dottilla myctiroides*, (b) *Emerita holthuisi*, (c) *Ceratonereis burmensis*, (d) *Heteromastus filiformis* and (e) *Metapenaeus dobsoni*.

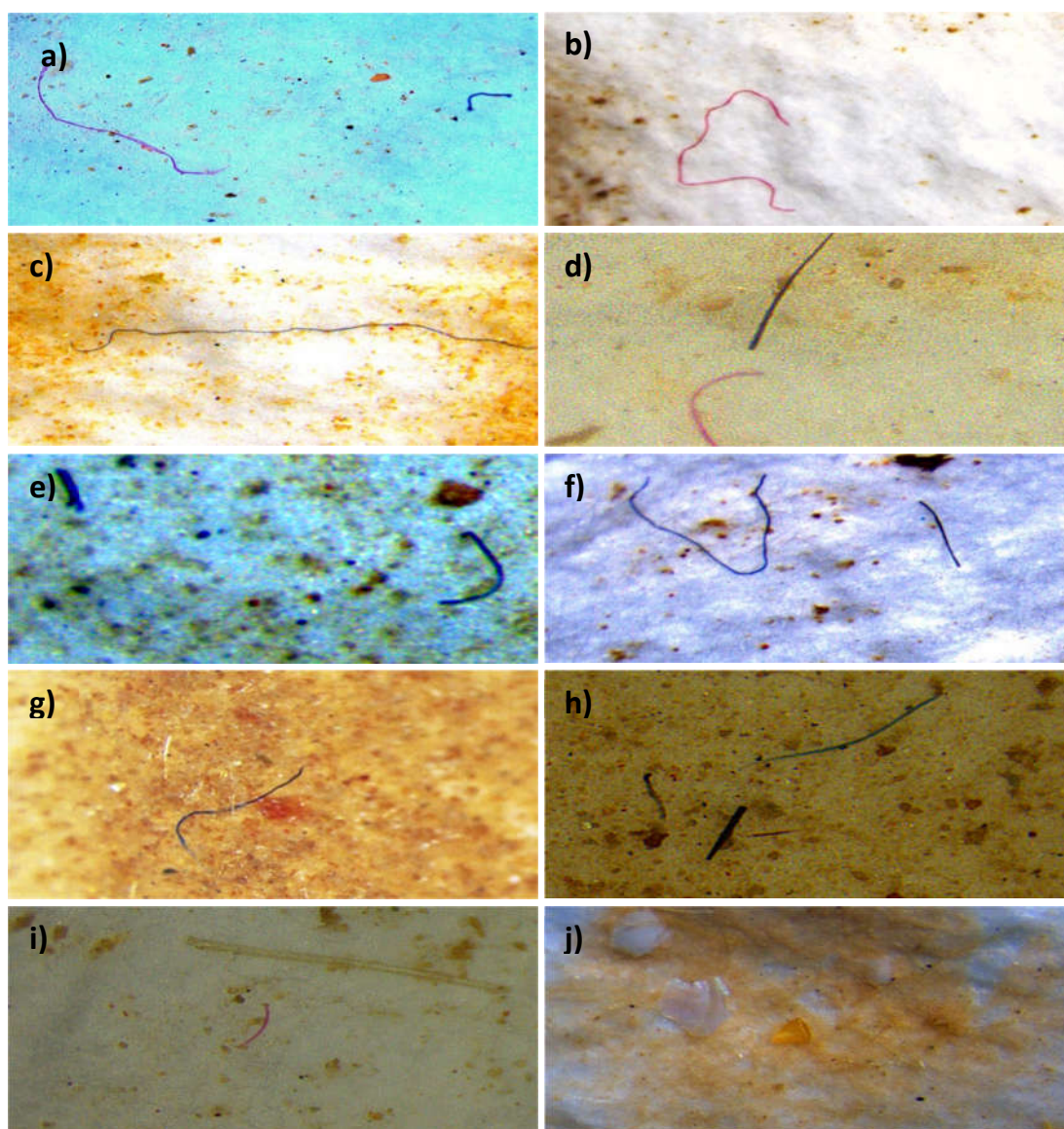


Figure 35. Microplastics in shorebird droppings samples observed under stereo-zoom microscope; **(a)** Eurasian Curlew, **(b)** Bar-tailed Godwit, **(c)** Whimbrel, **(d)** Common Greenshank, **(e)** Common Redshank, **(f)** Sanderling, **(g)** Common Sandpiper, **(h)** Greater Sand Plover, **(i)** Tibetan Sand Plover and **(j)** Kentish Plover.

Distribution pattern of microplastics

Network analysis revealed that water is the primary source of microplastics reaching the other ecosystem compartments (Figure 36). Different shorebird species had varying levels of microplastics, and it is clear that these particles were spread from the abiotic factors such as water and sediments and also through the food chain from their primary prey items (Figure 37).

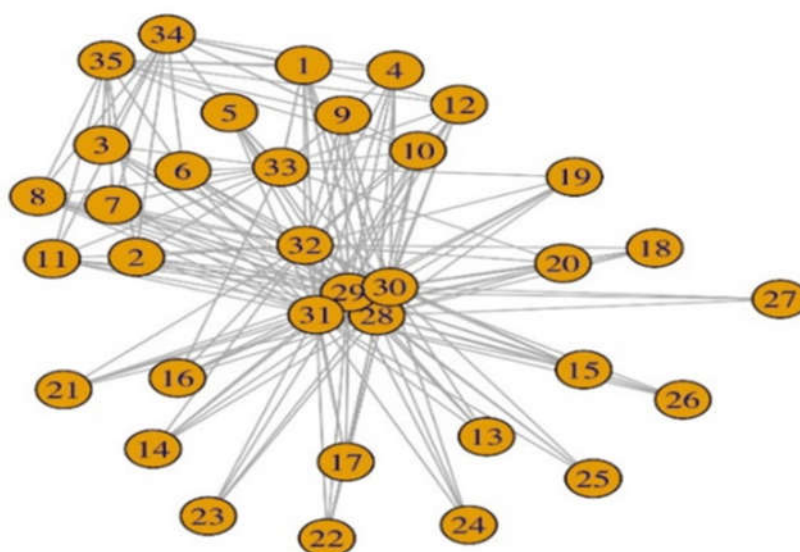


Figure 36. Co-occurrence network showing the microplastic distribution in water (1,2,4,5,9,10,28,29,30,31,32,33) sediment (3,6,7,8,11,12,34,35), Prey; *Dottilla myctiroides* (13), *Ceratonereis burmensis* (15), *Heteromastus filiformis* (14), *Emerita holthuisi* (16), *Metapenaeus dobsoni* (22), and in Shorebirds; Eurasian Curlew (17), Bar-tailed Godwit (20), Whimbrel (19), Common Greenshank (18), Common Redshank (24), Sanderling (25), Common Sandpiper (26), Greater Sand Plover (21), Tibetan Sand Plover (23) and Kentish Plover (27).

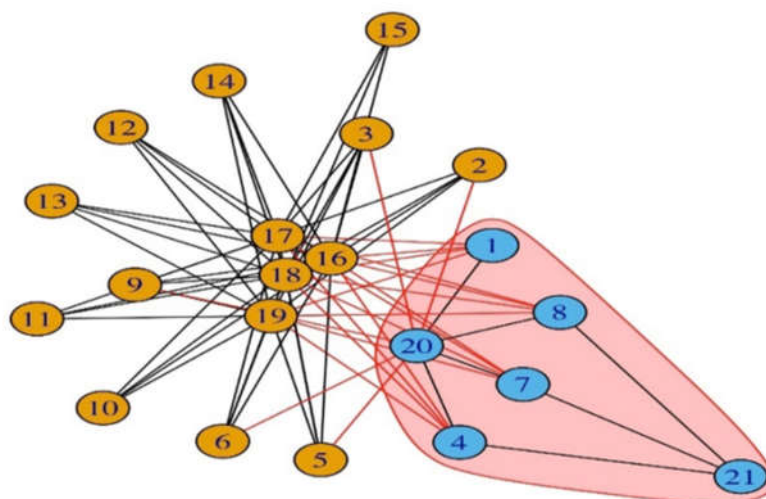


Figure 37. Co-occurrence network showing the distribution of microplastics in shorebirds and their prey; *Dottilla myctiroides* (1, 19), *Ceratonereis burmensis* (8), *Heteromastus filiformis* (16), *Emerita holthuisi* (3, 17), *Metapenaeus dobsoni* (4, 20) and in Shorebirds; Eurasian Curlew (17,21), Bar-tailed Godwit (20), Whimbrel (19), Common Greenshank (5), Common Redshank (13), Sanderling (14), Common Sandpiper (15), Greater Sand Plover (12), Tibetan Sand Plover (10) and Kentish Plover (9). The figure depicts two distinct communities. The first community, represented by blue circles enveloped in pink, exhibits correlations with both prey and predator species. The red lines represent linkages between the two communities, indicating connections and interactions between them.

The size of the microplastics in sediments ranged mostly between 1 mm and 3 mm (49.13%) and fibres smaller than 1 mm (5.93%) were also documented. The most abundant polymer observed in sediment was polyethylene (58.6%). Meanwhile, in water samples, the size of microplastics were higher than that in sediment samples ranging mostly between 2 mm and 5 mm (64.86%) and even higher than 5 mm in some cases. Polyethylene (47.5%) and polypropylene (28.3%) was found to be the most abundant polymers present in water samples. In the prey samples, microplastic fibres less than 2mm were observed and was most abundant in polychaete species, especially *Ceratonereis burmensis*, collected from KVCR mudflats (Figure 37).

PCA shows that there is clear delineations of the sediment and water on holding the microplastics. The highly contributed plastics did not show any particular orientations, but the <0.1, 0.1-0.2 mm suggested a relation with sediment, whereas water was more related with 0.3-0.4 mm, with less contributions than the sediments (Figure 38).

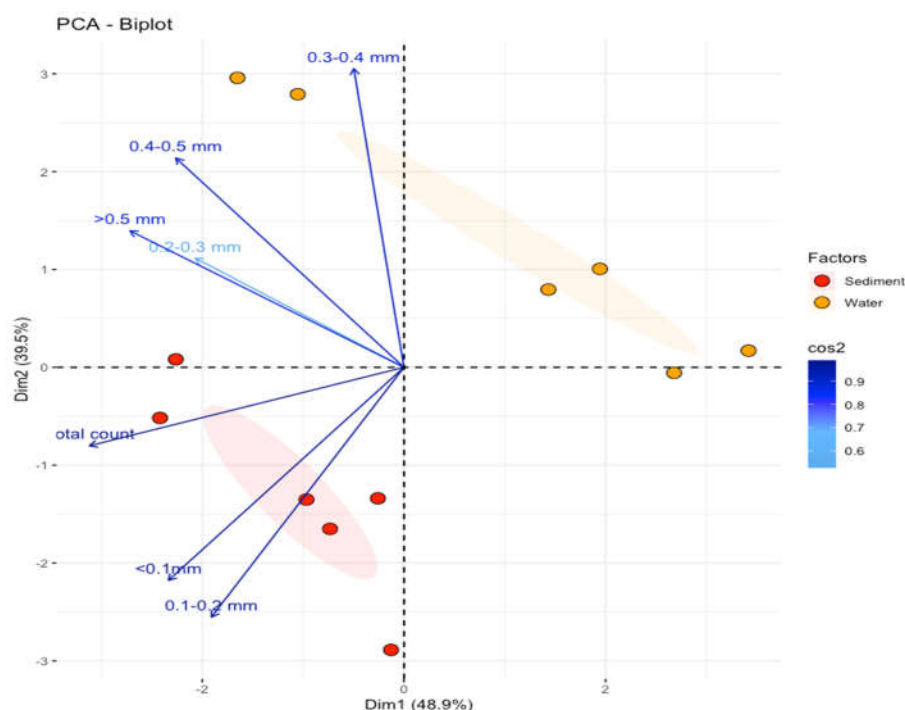


Figure 38. The PCA biplot showing sediment and water with different size ranges of microplastics. The red and pale yellow represent microplastics in sediment and water samples, respectively. The cos2 scale provides a measure of the relevance of each variable to the PCA.

All the prey species did not show any orientations to any size of the microplastics, although *Ceratonereis burmensis* showed an orientation to the 0.1 mm microplastics (Figure 39). Different size ranges of microplastics (<0.1 mm, 0.1-0.2 mm, 0.2-0.3 mm, 0.3-0.4 mm) obtained from the shorebird's droppings samples, where the <0.1 mm microplastics dominated the most (Figure 39). The Common Redshank, Common Sandpiper, Sanderling, Greater Sand Plover, Tibetan Sand Plover, and Kentish Plover showed orientation towards the 0.1 mm microplastics. The Eurasian Curlew delineated towards the 0.1–0.2 mm size range, whereas the Bar-tailed Godwit exhibited more orientation towards the size range of 0.3–0.4 mm (Figure 39).

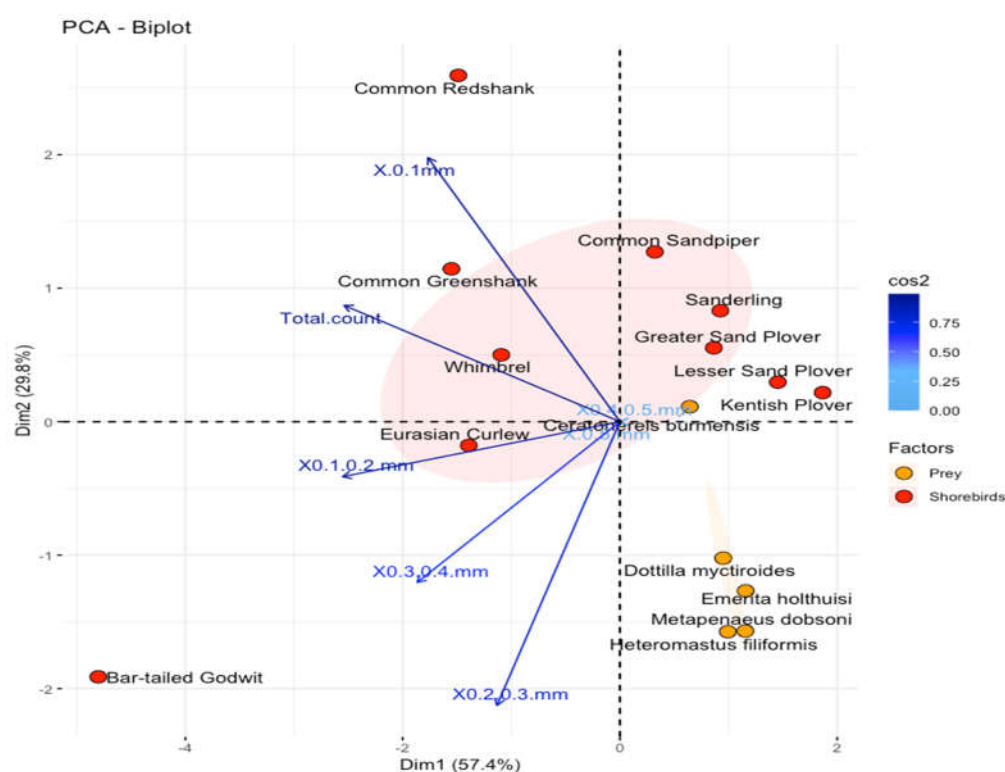


Figure 39. The PCA biplot showing the orientation of shorebirds and their prey towards different size ranges of microplastics. The pale yellow and red colour represent macrobenthic prey and shorebirds, respectively. The cos2 scale provides a measure of the relevance of each variable to the PCA.

The highest abundance of microplastic particles was reported in the sediment samples (55.7%) followed by water samples (42.9%). Further, microplastic particles mostly of size below 1 mm (68.92%) were reported from the droppings of all the 10 different species of shorebirds from the study area (Figure 39). Interestingly, microfibrs bigger than 1 mm were observed in the samples of Bar-tailed Godwit from KVCR mudflats and Whimbrel from KVCR sand beaches.

Concentration of heavy metals in shorebird droppings

Cr was the most prevalent heavy metal in droppings of shorebirds collected from mangroves (Table 18), with the Common Sandpiper showing the highest Cr content (77.21 ± 2.82 mg/kg). While the droppings of Kentish Plover had the highest level of Zn (75.15 ± 0.21 mg/kg) and the lowest being Co (17.37 ± 0.13 mg/kg) and Pb (16.26 ± 0.05 mg/kg) than all other species. On the other hand, Bar-tailed Godwit and Common Sandpiper had lowest concentrations of Zn (24.64 ± 2.12 and 21.24 ± 0.32 mg/kg respectively) followed by Co (25.60 ± 0.93 and 25.68 ± 1.65 mg/kg respectively). Common Greenshank had the highest concentration of Cd (6.67 ± 0.55 mg/kg), while Common Redshank had the highest concentrations of Cu (85.58 ± 3.71 mg/kg). The highest Pb content (55.25 ± 1.17 mg/kg) was recorded in Common Sandpiper, which is much closer to that reported in Eurasian Curlew (55.24 ± 1.56 mg/kg). The Tibetan Sand Plover, Greater Sand Plover and Kentish Plover had comparatively lower concentrations of Pb (17.47 ± 2.00 mg/kg, 19.32 ± 0.11 mg/kg and 16.26 ± 0.05 mg/kg respectively) and Cd (1.69 ± 0.22 mg/kg, 4.45 ± 0.19 mg/kg and 2.65 ± 0.24 mg/kg respectively) in their droppings than other species tested. The most abundant heavy metal in Tibetan Sand Plover and Greater Sand Plover was Cr (61.32 ± 6.88 mg/kg and 61.32 ± 6.88 mg/kg respectively). The droppings of Whimbrel had high concentrations of Zn, Co, Cr and Cd (42.52 ± 20.96 mg/kg, 51.16 ± 4.19 mg/kg, 64.83 ± 3.48 mg/kg and 3.58 ± 3.38 mg/kg respectively). In mudflats, Zn levels were highest in Kentish Plover (73.79 ± 2.48 mg/kg) followed by Tibetan Sand Plover (65.53 ± 3.62 mg/kg) and Eurasian Curlew

(63.93 ± 3.20 mg/kg). Cu was also highest in Kentish Plover (43.56 ± 1.20 mg/kg) and that of Co, Cr, Pb and Cd was highest in Eurasian Curlew (62.20 ± 6.10 mg/kg, 76.85 ± 1.48 mg/kg, 61.11 ± 4.19 mg/kg and 9.11 ± 0.37 mg/kg respectively). The droppings samples from the mudflats generally had higher concentrations of Cr (Table 18). In sand beaches, Cu was highest in Common Redshank (85.40 ± 2.95 mg/kg) and Cd was highest in Common Greenshank (18.37 ± 1.97 mg/kg). The other metals, Zn, Co, Cr and Pb were the highest in Eurasian Curlew (78.31 ± 1.37 mg/kg, 67.23 ± 1.73 mg/kg, 86.84 ± 0.58 mg/kg, 65.21 ± 1.58 mg/kg) (Table 18).

The principal component analysis (PCA) conducted on the complete samples unveiled distinct patterns of heavy metal concentration across various shorebird species (Figure 40). Zn was identified as the most abundant element in Kentish Plover and Eurasian Curlew. Conversely, Sanderling and Bar-tailed Godwit displayed the lowest Zn concentrations. Cu showed a contrasting distribution, with Common Greenshank having the highest abundance and Sanderling and Bar-tailed Godwit again exhibiting the lowest levels. Co exhibited a more uniform distribution, with higher concentrations observed across most species. Notably, Eurasian Curlew, Whimbrel, and Common Greenshank displayed the highest concentration of Co, with the Bar-tailed Godwit exhibiting the lowest levels. Cr was present in similar quantities across all shorebird species, with the highest levels found in Sanderling and Eurasian Curlew. Pb was concentrated primarily in droppings of Eurasian Curlew, with comparable quantities also detected in Bar-tailed Godwit, Common Greenshank, Common Redshank, and Common Sandpiper. Cd was found at considerably lower levels compared to other heavy metals, exhibiting relatively consistent concentrations across all species.

Table 18. Mean ($\pm$ SD) heavy metal concentrations (mg/kg) in ten species of shorebird droppings in each habitat type.

Habitats	Shorebird species	Zinc (Zn)	Copper (Cu)	Cobalt (Co)	Chromium (Cr)	Lead (Pb)	Cadmium (Cd)
Mudflats	Tibetan Sand Plover	65.53 $\pm$ 3.62	24.37 $\pm$ 9.44	23.78 $\pm$ 15.29	59.09 $\pm$ 6.11	15.34 $\pm$ 1.96	0.96 $\pm$ 0.69
	Greater Sand Plover	34.51 $\pm$ 3.36	24.67 $\pm$ 8.26	27.59 $\pm$ 7.87	72.98 $\pm$ 6.09	21.30 $\pm$ 7.11	2.36 $\pm$ 1.38
	Kentish Plover	73.79 $\pm$ 2.48	43.56 $\pm$ 1.20	17.88 $\pm$ 2.03	58.05 $\pm$ 4.30	16.37 $\pm$ 1.97	2.03 $\pm$ 0.55
	Common Redshank	37.34 $\pm$ 6.75	36.28 $\pm$ 25.22	28.65 $\pm$ 12.49	55.42 $\pm$ 3.88	37.22 $\pm$ 8.71	3.30 $\pm$ 2.65
	Common Greenshank	36.70 $\pm$ 6.57	38.07 $\pm$ 10.89	31.92 $\pm$ 14.60	65.95 $\pm$ 3.46	44.57 $\pm$ 8.20	2.69 $\pm$ 3.30
	Common Sandpiper	22.27 $\pm$ 2.44	28.62 $\pm$ 19.01	27.22 $\pm$ 6.97	61.52 $\pm$ 16.94	45.25 $\pm$ 1.18	2.43 $\pm$ 2.35
	Bar-tailed Godwit	23.44 $\pm$ 1.57	22.35 $\pm$ 5.18	24.34 $\pm$ 1.44	59.01 $\pm$ 2.09	43.07 $\pm$ 6.00	6.87 $\pm$ 1.90
	Whimbrel	42.52 $\pm$ 20.96	29.25 $\pm$ 11.35	51.16 $\pm$ 4.19	64.83 $\pm$ 3.48	42.73 $\pm$ 8.88	3.58 $\pm$ 3.38
	Eurasian Curlew	63.93 $\pm$ 3.20	18.03 $\pm$ 2.32	62.20 $\pm$ 6.10	76.85 $\pm$ 1.48	61.11 $\pm$ 4.19	9.11 $\pm$ 0.37
Mangroves	Tibetan Sand Plover	48.60 $\pm$ 21.50	28.29 $\pm$ 8.16	37.56 $\pm$ 10.52	61.32 $\pm$ 6.88	17.47 $\pm$ 2.00	1.69 $\pm$ 0.22
	Greater Sand Plover	35.70 $\pm$ 3.30	32.75 $\pm$ 4.62	30.44 $\pm$ 4.93	76.14 $\pm$ 2.90	19.32 $\pm$ 0.11	4.45 $\pm$ 0.19
	Kentish Plover	75.15 $\pm$ 0.47	44.97 $\pm$ 0.64	17.37 $\pm$ 0.13	60.38 $\pm$ 0.31	16.26 $\pm$ 0.05	2.65 $\pm$ 0.24
	Common Redshank	45.69 $\pm$ 3.27	85.58 $\pm$ 3.71	33.84 $\pm$ 2.00	59.72 $\pm$ 1.04	53.30 $\pm$ 0.14	5.79 $\pm$ 0.58
	Common Greenshank	43.09 $\pm$ 2.59	43.57 $\pm$ 1.38	35.36 $\pm$ 0.77	66.02 $\pm$ 0.64	46.19 $\pm$ 2.51	6.67 $\pm$ 0.55
	Common Sandpiper	21.24 $\pm$ 0.32	54.94 $\pm$ 2.98	25.68 $\pm$ 1.65	77.21 $\pm$ 2.82	55.25 $\pm$ 1.17	6.42 $\pm$ 0.32
	Bar-tailed Godwit	24.64 $\pm$ 2.12	23.05 $\pm$ 3.11	25.60 $\pm$ 0.93	56.63 $\pm$ 2.47	45.28 $\pm$ 2.64	6.61 $\pm$ 0.63
	Whimbrel	65.98 $\pm$ 3.67	37.32 $\pm$ 1.81	53.52 $\pm$ 0.50	61.45 $\pm$ 0.25	45.44 $\pm$ 1.18	6.45 $\pm$ 0.26
	Eurasian Curlew	67.31 $\pm$ 1.31	36.28 $\pm$ 2.69	57.23 $\pm$ 1.73	76.84 $\pm$ 0.56	55.24 $\pm$ 1.56	6.24 $\pm$ 0.17
Sandy beaches	Tibetan Sand Plover	51.13 $\pm$ 3.29	51.17 $\pm$ 7.49	51.04 $\pm$ 3.64	43.93 $\pm$ 7.11	20.50 $\pm$ 16.03	14.20 $\pm$ 1.41
	Greater Sand Plover	55.56 $\pm$ 3.33	37.09 $\pm$ 2.06	53.05 $\pm$ 5.15	20.40 $\pm$ 8.48	25.56 $\pm$ 4.15	11.88 $\pm$ 2.73
	Kentish Plover	41.09 $\pm$ 7.26	34.18 $\pm$ 1.89	50.80 $\pm$ 5.57	82.16 $\pm$ 8.26	-	7.04 $\pm$ 0.04
	Common Redshank	46.09 $\pm$ 3.00	85.40 $\pm$ 2.95	34.64 $\pm$ 2.01	59.91 $\pm$ 1.45	54.50 $\pm$ 0.48	5.78 $\pm$ 0.83
	Common Greenshank	46.23 $\pm$ 6.23	47.43 $\pm$ 2.63	56.90 $\pm$ 5.77	51.55 $\pm$ 2.91	30.61 $\pm$ 3.83	18.37 $\pm$ 1.97
	Common Sandpiper	22.31 $\pm$ 2.34	55.31 $\pm$ 2.93	37.12 $\pm$ 1.78	75.63 $\pm$ 3.42	55.48 $\pm$ 1.91	5.79 $\pm$ 0.55
	Bar-tailed Godwit	24.78 $\pm$ 1.56	23.77 $\pm$ 3.89	26.17 $\pm$ 1.59	57.45 $\pm$ 1.84	45.52 $\pm$ 1.71	6.96 $\pm$ 0.719
	Whimbrel	62.03 $\pm$ 4.08	44.27 $\pm$ 10.59	47.98 $\pm$ 5.91	45.83 $\pm$ 7.61	16.33 $\pm$ 1.60	5.63 $\pm$ 2.19
	Eurasian Curlew	78.31 $\pm$ 1.37	46.30 $\pm$ 2.69	67.23 $\pm$ 1.73	86.84 $\pm$ 0.58	65.21 $\pm$ 1.58	7.25 $\pm$ 0.19
	Sanderling	15.54 $\pm$ 1.21	15.12 $\pm$ 1.56	39.06 $\pm$ 4.95	80.85 $\pm$ 2.87	16.39 $\pm$ 1.34	9.31 $\pm$ 0.48

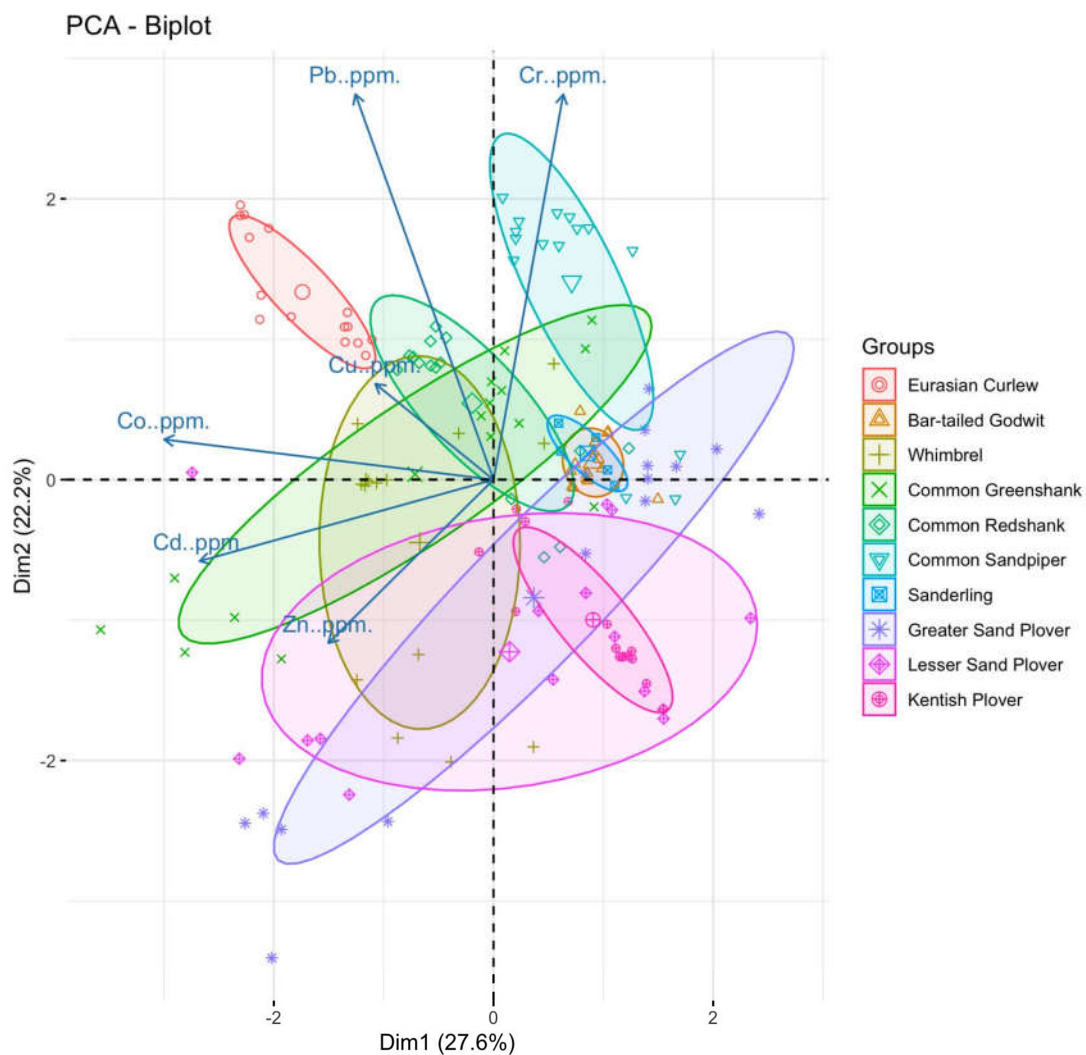


Figure 40. PCA showing the variation in concentration of heavy metals, Zn, Cu, Co, Cr, Pb and Cd across the selected ten shorebird species. Different species are represented by different unique coloured symbols. The PCA highlights different clustering patterns, highlighting species specific differences in heavy metal accumulation.

The two-way ANOVA results reveal significant effects of habitat, species, and their interaction on heavy metal concentrations in shorebird droppings across mudflats, mangroves, and sand beaches. For Zn, although habitat effects were marginally significant, species and their interaction with habitat exhibited strong significance. Cu, Co, Cr, Pb and Cd levels were significantly influenced by habitat and species, with a pronounced interaction. Post-hoc analysis revealed significant habitat variations for heavy metals. Zn and Pb concentrations did not differ significantly across habitats. In contrast, Cu, Co and Cd exhibited significant habitat variations.

Specifically, Cu and Co levels were highest at mudflats while Cd concentration dominated in sand beaches. Cr concentrations did not show significant variation between mudflats and sand beaches, though a marginal significance was observed between mangroves and sand beaches (Figure 41).

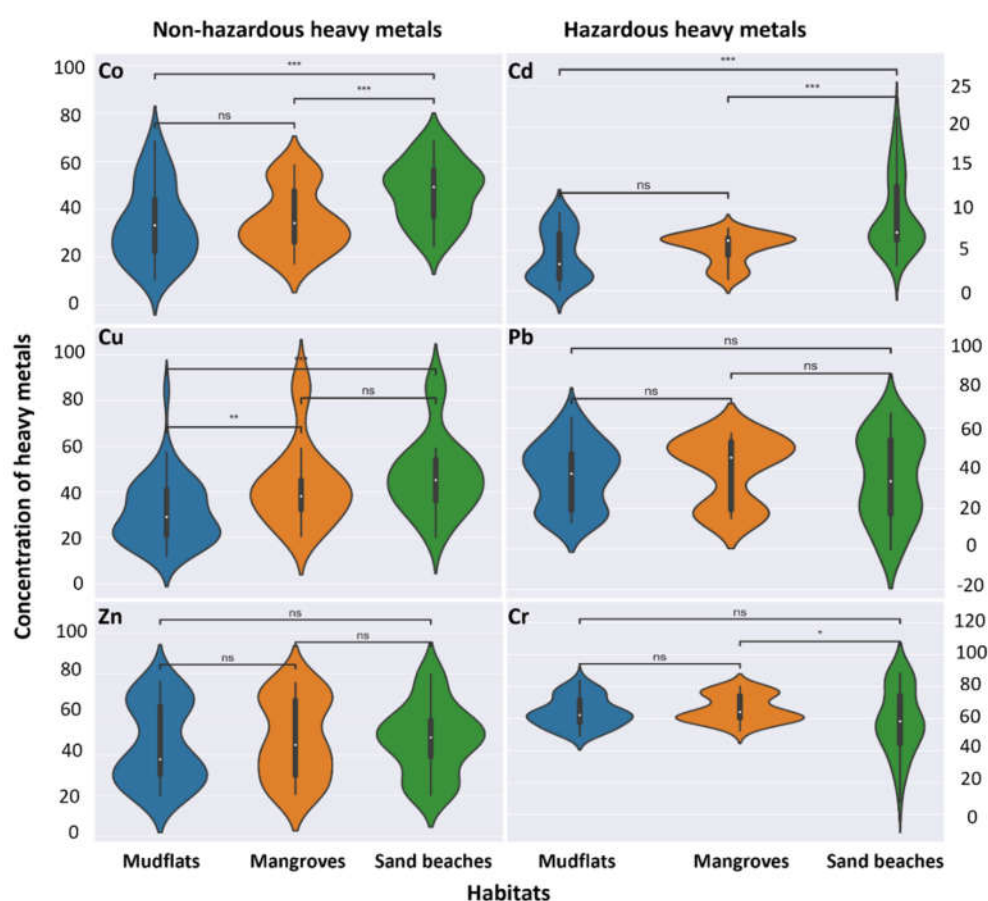
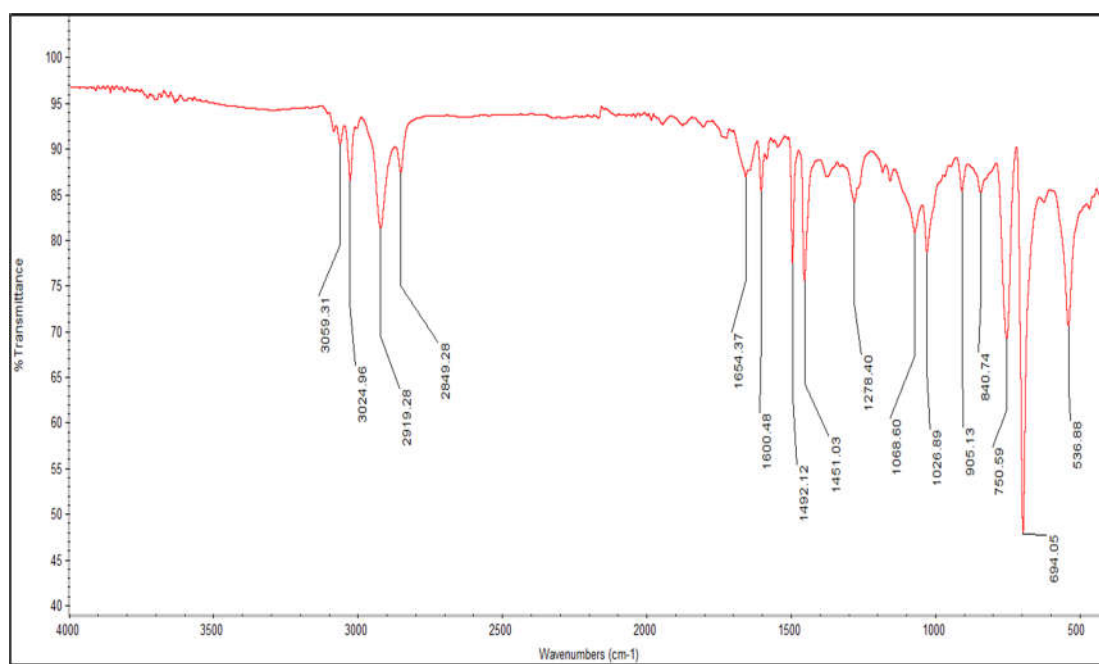


Figure 41. Habitat-specific variations in different non-hazardous (Zn, Cu, Co) and hazardous (Cr, Pb, Cd) heavy metals. Non-hazardous heavy metals are depicted with a uniform scale (0 to 100 mg/kg), whereas the other hazardous heavy metals are displayed on distinct scales: Cr (0 to 120 mg/kg), Pb (-20 to 100 mg/kg) and Cd (0 to 25 mg/kg). Each plot illustrates the variation in heavy metal concentration across mudflats, mangroves and sand beaches and highlights significant variations detected through post hoc analysis (ns: non-significant, *: p < 0.05; **: p < 0.01, ***: p < 0.0001).

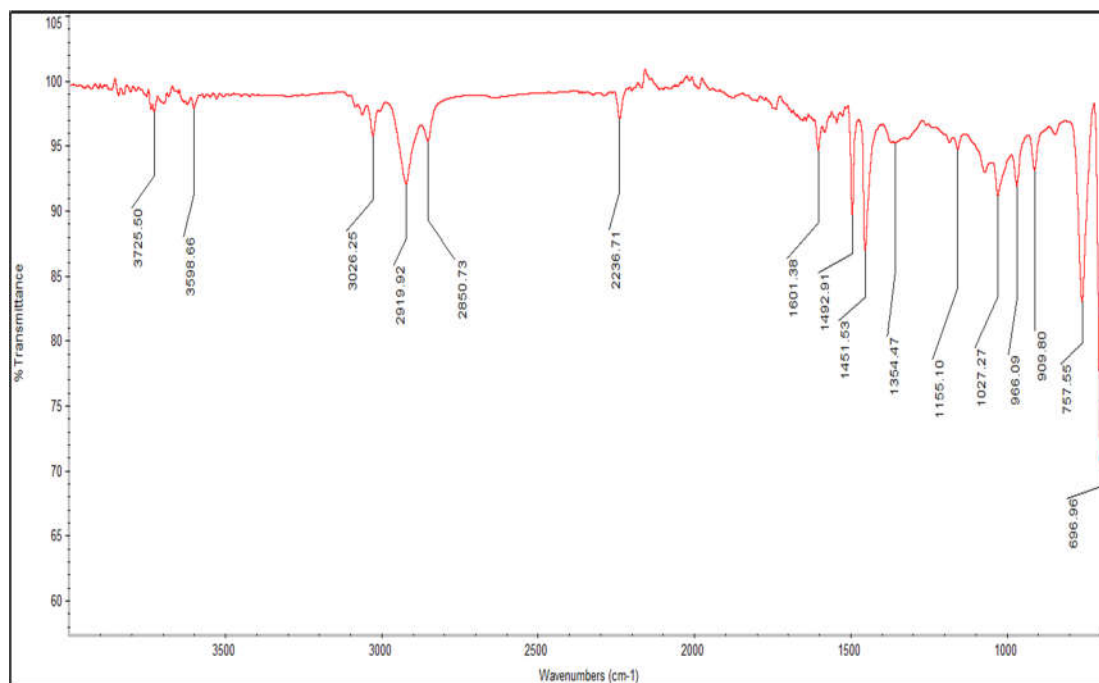
Concentration of microplastic polymers in shorebird droppings

Polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), nitrile and polyethylene terephthalate (PET) were the polymers identified in shorebird's droppings samples (Figure 42).

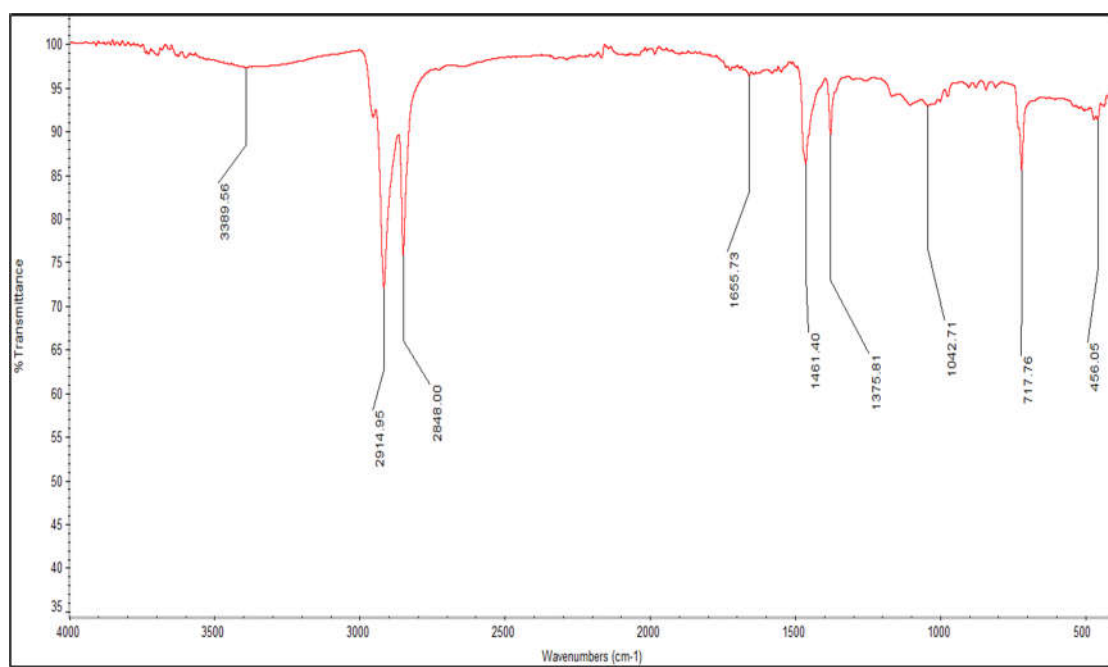
a)



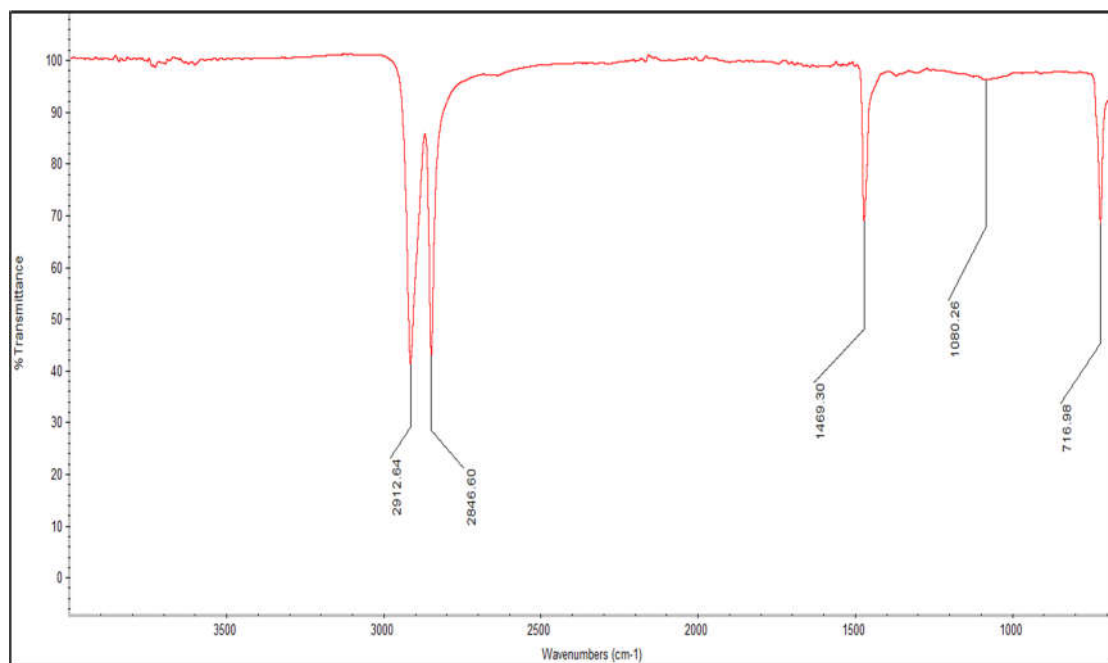
b)



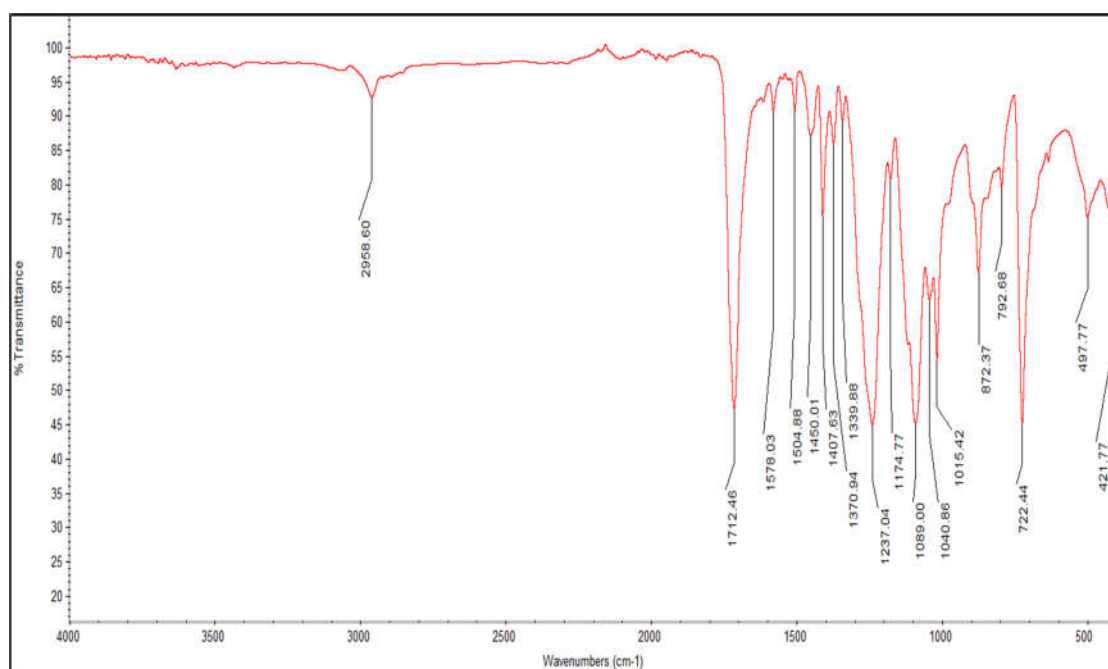
c)



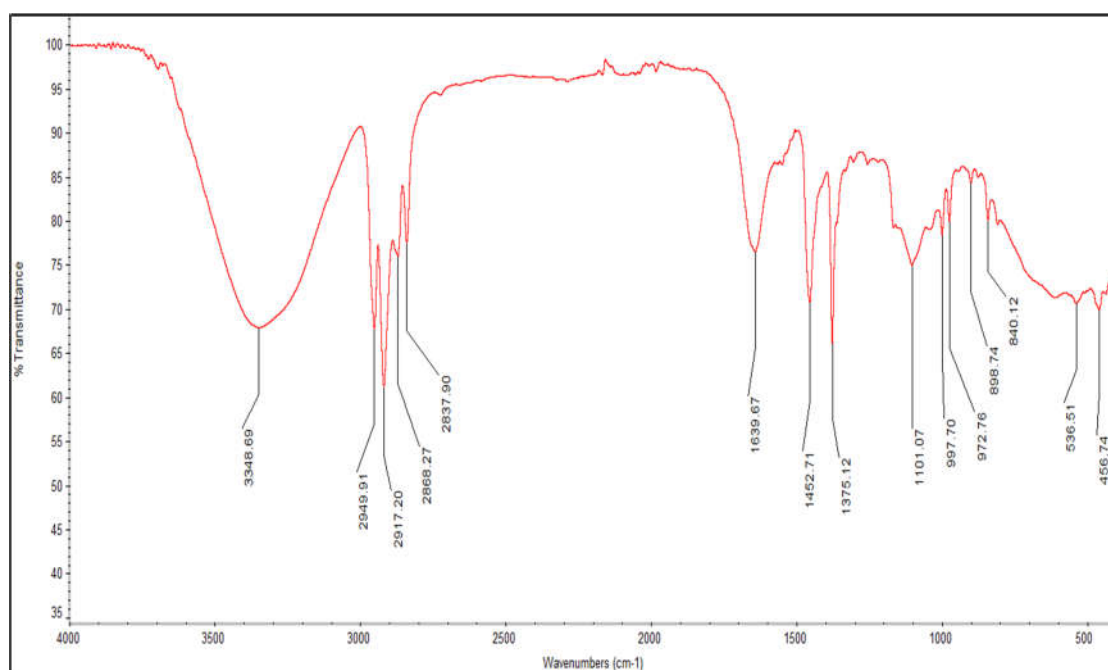
d)



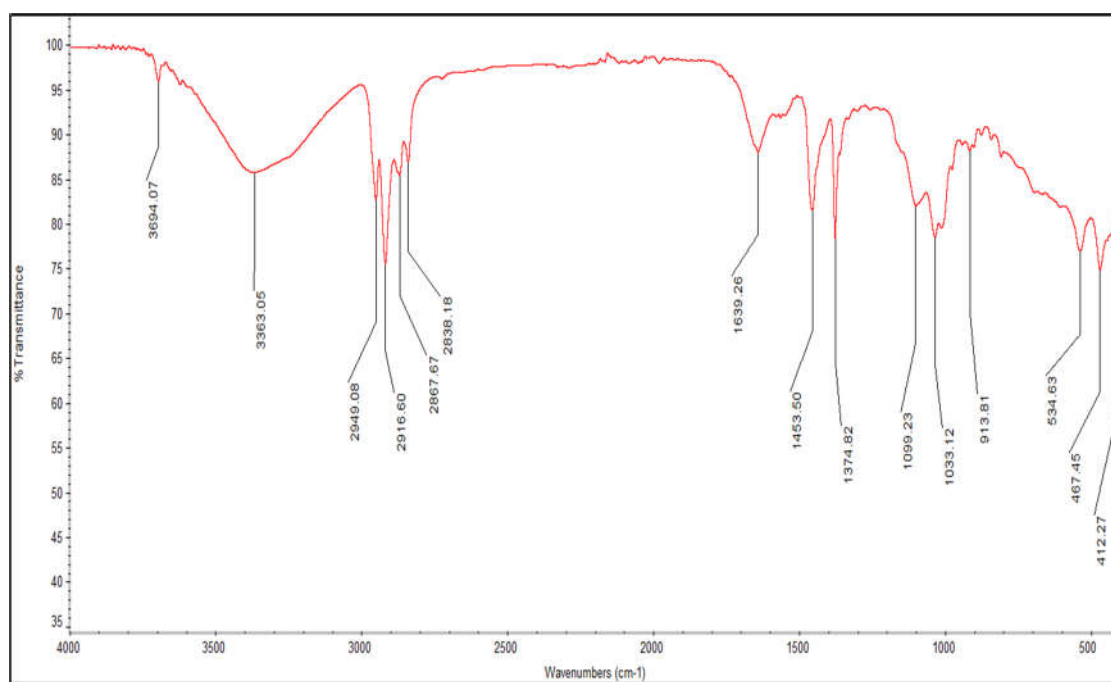
e)



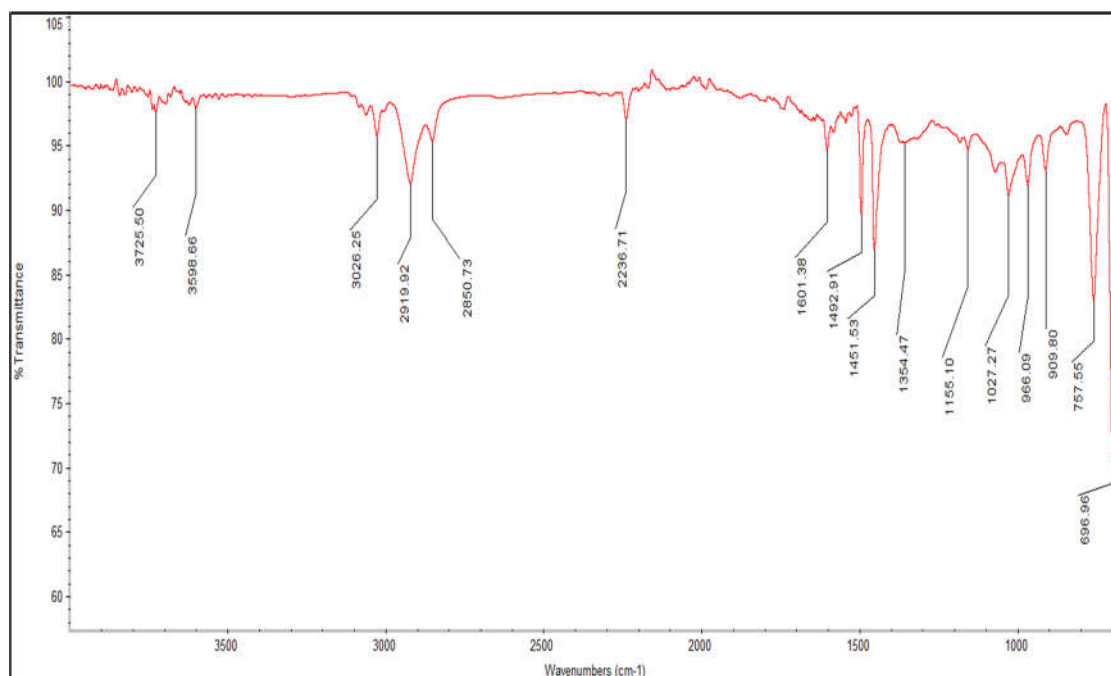
f)



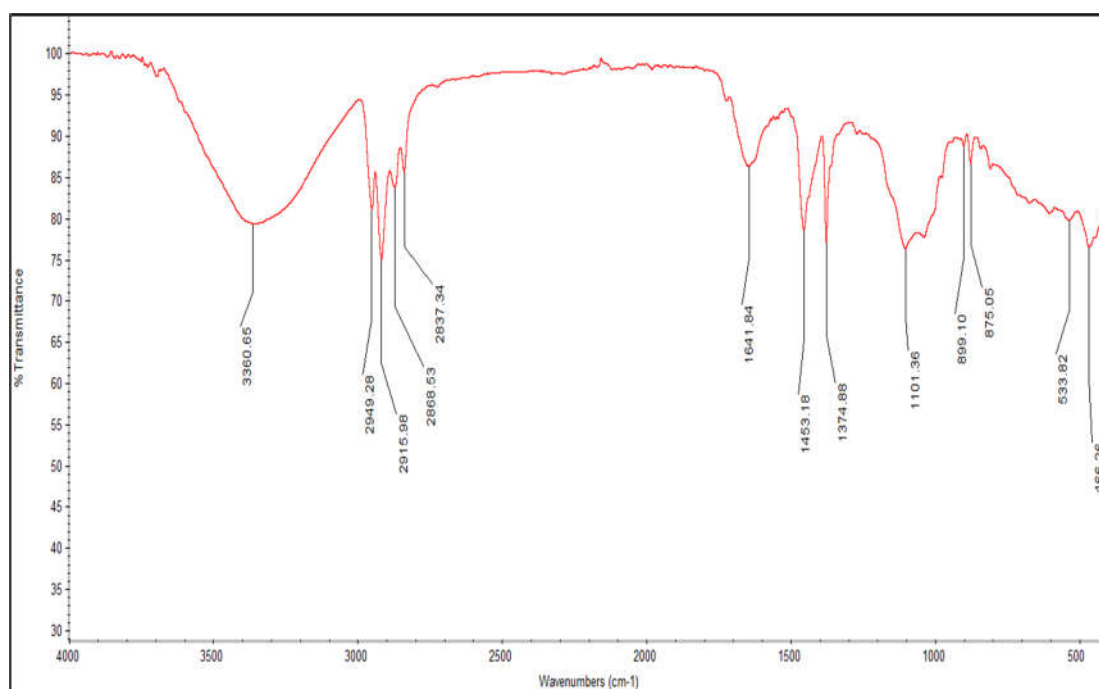
g)



h)



i)



j)

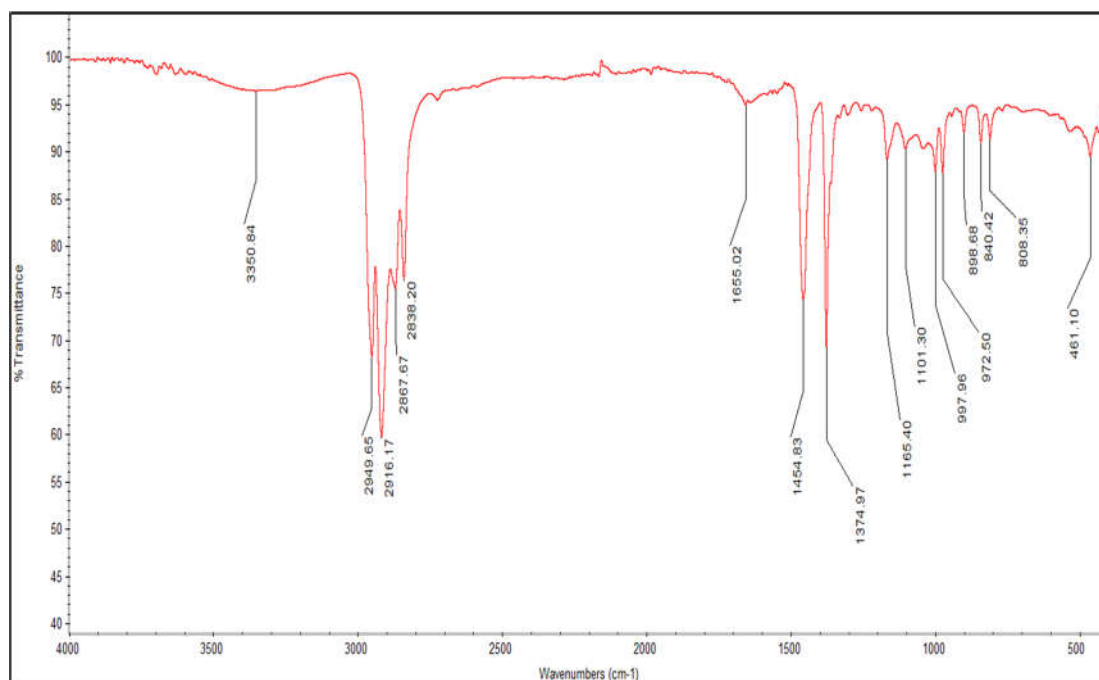


Figure 42. FTIR spectra of various polymers obtained from the droppings sample of shorebirds; **(a)** PS in Eurasian Curlew, **(b)** PS in Bar-tailed Godwit, **(c)** PE in Whimbrel, **(d)** PE in Common Greenshank, **(e)** PET in Common Redshank, **(f)** PP in Sanderling, **(g)** PP in Common Sandpiper, **(h)** Nitrile in Greater Sand Plover, **(i)** PP in Tibetan Sand Plover and **(j)** PP in Kentish Plover respectively.

Different shorebird species had varying levels of polymers (Figure 43). The most observed polymer type was PS (42.6%), followed by PE (32.2%), PP (12.86%), PVC (5.17%), Nitrile (4.78%) and PET (2.39%) (Fig.2). Polyethylene was found to be the most abundant in Common Greenshank (22.7%), followed by Common Redshank (18.9%) and the least abundant in Tibetan Sand Plover and Kentish Plover (1.2%). The Bar-tailed Godwit (18.75%) had the highest concentration of PP, though other species did not have much of a difference. The most abundant PS was the highest in droppings samples of Bar-tailed Godwit (23.6%), followed by Common Greenshank (17.2%), Eurasian Curlew (16.1%) and Whimbrel (10.7%) and the least in Kentish Plover (3.2%). PVC was found in six species and the most abundant in Common Redshank. Nitrile was identified in seven species and PET in three species.



Figure 43. The percentage of abundance of different polymer types identified in the microplastics obtained from the droppings of shorebirds.

Relationship between Heavy metals and Microplastics in shorebirds

The near-threatened species, Eurasian Curlew and Bar-tailed Godwit revealed a significant co-occurrence of microplastics with the hazardous heavy metals Cr and Pb. Although, this pattern was not evident for the other heavy metals analysed in Bar-tailed Godwit. The biofilm-grazing Sanderling displayed an unexpected pattern of high Cr levels despite low microplastic abundance. The planktivorous Common Redshank and Common Greenshank displayed a degree of co-occurrence,

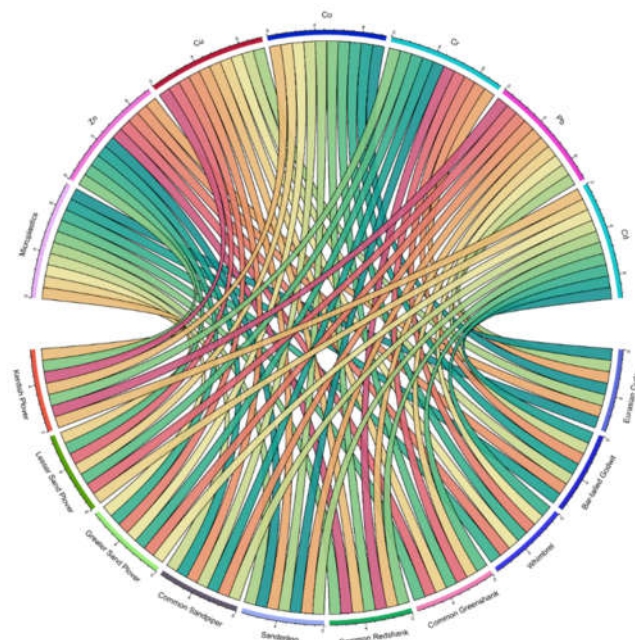


Figure 44. Relationship between heavy metal concentration and microplastic abundance in migratory shorebird community. Shorebird species, types of heavy metals and microplastics were represented by different coloured segments on the outer ring. Coloured lines connecting the segments shows the relationship of each pollutant (measured on a percentage scale from 0 to 10) to each shorebird species.

Spatial and Temporal Variability of microplastic abundance in water and sediment

Microplastic abundance in water and sediment samples, exhibited significant variation across different habitats (Table 19). Microplastic levels were highest in mangroves and lowest in sand beaches. Mudflats also showed a notable presence of microplastics, although less than that found in mangroves. Within sand beaches, microplastic abundance in water was highest at Pulimudu beach and lowest at Kappad beach. Thikkodi and Pulimudu beach had the highest sediment microplastic levels, and Elathur and Kappad beaches had the lowest. The abundance of microplastics in both water and sediment exhibited significant annual variation, with the lowest levels observed in 2021 and the highest in 2022 (Table 19, Figure 45a). Seasonally, the microplastic abundance peaked during the monsoon season, and lowest during the pre-monsoon season (Table 19).

Table 19. Mean $\pm$ (SE) of microplastics abundance (number of particles) in water and sediment across different study sites, years and seasons. (ANOVA results: $p < 0.01$ indicates statistical significance. Units: Water: particles/L; Sediment: particles/250 g (wet weight))

Water (units: particles/L)		
Sites	Mudflats	346.5 $\pm$ 172.1
	Mangroves	367.42 $\pm$ 122.7
	Pulimudu beach	209.2 $\pm$ 87.2
	Ariyallur beach	174 $\pm$ 126.03
	Elathur beach	123.2 $\pm$ 52.9
	Korappuzha beach	188.1 $\pm$ 116.05
	Kappad beach	101 $\pm$ 38.4
	Iringal beach	193.7 $\pm$ 89.7
	Thikkodi beach	202.1 $\pm$ 69.9
	Kolavippalam beach	151 $\pm$ 70.1
	ANOVA (one way)	F_(9,60) = 5.11; $p < 0.01$
Year	2020	184.9 $\pm$ 76.64
	2021	174.23 $\pm$ 82.53
	2022	273.55 $\pm$ 186.5
	ANOVA (one way)	F_(9,60) = 6.116; $p < 0.02$
Season	Pre-monsoon	144.1 $\pm$ 73.54
	Monsoon	273.86 $\pm$ 147.4
	Post-monsoon	164.9 $\pm$ 79
	ANOVA (one way)	F_(9,60) = 4.44; $p < 0.01$
Sediment (wet weight) (Unit: particles/250 g)		
Sites	Mudflats	308.5 $\pm$ 116.1
	Mangroves	424.1 $\pm$ 116.1
	Pulimudu beach	289.8 $\pm$ 89.4
	Ariyallur beach	210.5 $\pm$ 64.6
	Elathur	145.2 $\pm$ 55.9
	Korappuzha	273.4 $\pm$ 105.8
	Kappad	138.5 $\pm$ 73.37
	Thikkodi	291.1 $\pm$ 141.2
	Iringal	280.2 $\pm$ 105
	Kolavippalam	237.5 $\pm$ 73.17
	ANOVA (one way)	F_(9,60) = 4.287; $p < 0.01$
Year	2020	232.75 $\pm$ 75.25
	2021	222.3 $\pm$ 71.9
	2022	343.55 $\pm$ 184.4
	ANOVA (one way)	F_(9,60) = 7.495; $p < 0.01$
Season	Pre-monsoon	216.1 $\pm$ 70.7
	Monsoon	322.5 $\pm$ 155.4
	Post-monsoon	212.65 $\pm$ 75.57
	ANOVA (one way)	F_(9,60) = 7.36; $p < 0.01$

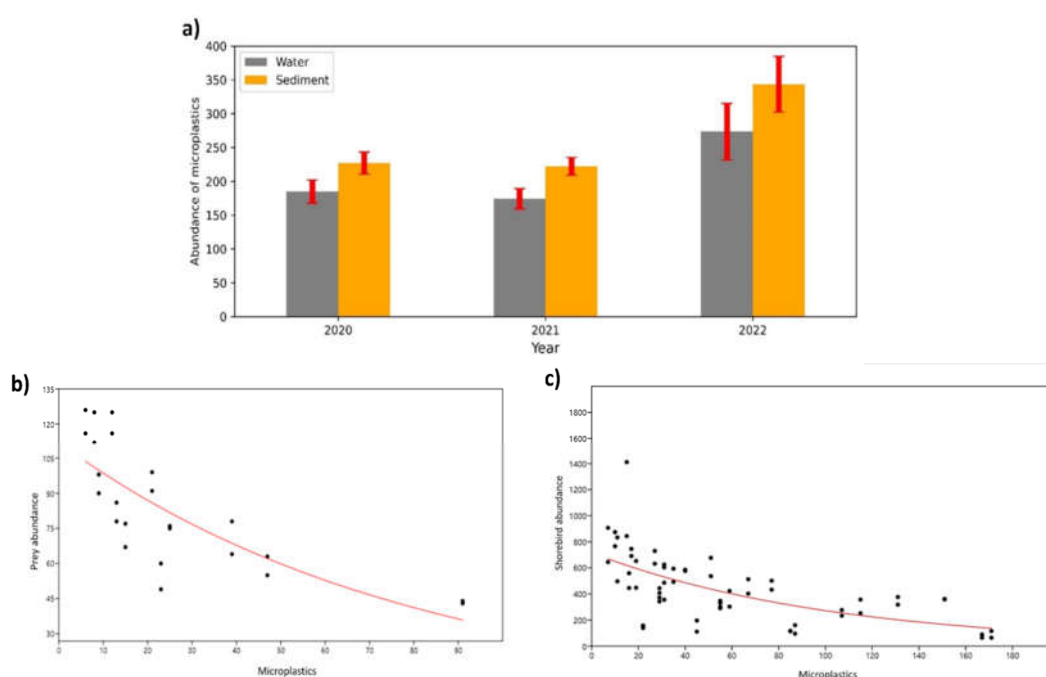


Figure 45. Annual variation in microplastic abundance on the west coast of India (2020-2022), **(a)** microplastic abundance in water and sediment samples, **(b)** negative correlation between microplastic abundance and prey abundance, **(c)** negative correlation between microplastic abundance and shorebird abundance.

Microplastics in biofilms, plankton and benthic macroinvertebrates

Microplastics were also observed in the collected samples of biofilms, phytoplankton, and zooplankton from the study areas (Table 20). The abundance of microplastics increased over the years in these biotic samples. Microplastics were found in all the benthic macroinvertebrate prey samples obtained and were increasing over the years (Table 21). Additionally, a declining trend in prey abundance was observed in the study area between 2020-2022 (Figure 45a). None of the independent variables in this model have a significant effect on the dependent variable abundance, according to the obtained p-values. The values far from zero in the deviation of residuals were obtained, indicating that the data is not well predicted. The intercept value was 3.331 (p-value: 0.997), indicating that it was not significant. The microplastic coefficient (-0.001553, p-value: 0.867) indicated a low negative effect on the abundance of prey (Figure 45b). The AIC value was low (183.8), indicating a better fit. All other independent variables also

had p-values greater than 0.05, indicating that none of them had a significant effect on the abundance of prey.

Table 20. Overall abundance (mean and SD) (number of particles) of various types of microplastics (fibres, fragments and granules) in all the investigated samples (water, sediment, biofilm, phytoplankton, zooplankton, benthic macroinvertebrates and shorebird droppings) (Units: water: particles/L; sediment: particles/250 g; macroinvertebrates: particles/5 g; phytoplankton, zooplankton, biofilms, and shorebird droppings: particles/g).

Type of sample	Total abundance of microplastics	Fibres	Fragments	Granules
Water	205.65 ± 126.28	159.29 ± 103.05	39.38 ± 43.18	6.28 ± 7.26
Sediment	259.94 ± 126.33	203.41 ± 106.44	42.48 ± 39.04	13.92 ± 19.3
Biofilm	28 ± 8.1	6.28 ± 1.16	13.14 ± 4.64	8.57 ± 2.32
Phytoplankton	24.14 ± 12.11	6.67 ± 3.09	10.34 ± 3.29	7.6 ± 6.79
Zooplankton	42.71 ± 15.94	27.3 ± 13.57	8.6 ± 3.85	7 ± 1.63
Macrobenthic prey	101.14 ± 45.58	56.5 ± 26.6	26.8 ± 11.6	17.7 ± 6.96
Shorebird droppings	243.57 ± 242.54	161 ± 165.6	43.4 ± 40.59	39.14 ± 35.8

Table 21. Abundance (mean and SD) (particles/5g) of various types of microplastics (fibres, fragments and granules) in all the types of benthic macroinvertebrates.

Type of sample	Habitat	Foraging mode	Total abundance of microplastics	Fibres	Fragments	Granules
Small crab	Mudflats/mangroves	Deposit feeding	21 ± 8.93	16 ± 7.48	2.6 ± 0.94	2.3 ± 0.47
Polychaetes	Mudflats/mangroves	Deposit feeding	53.3 ± 26.93	30 ± 14.96	4.6 ± 2.49	5 ± 2.94
Shrimp	Mudflats/mangroves	Scavenging/deposit feeding	16.33 ± 7.49	7 ± 3.74	5.3 ± 2.05	4 ± 1.63
Cosmonotus crab	Sand Beaches	Suspension feeding	12.33 ± 5.85	4.6 ± 2.49	1 ± 0.81	6.6 ± 2.49

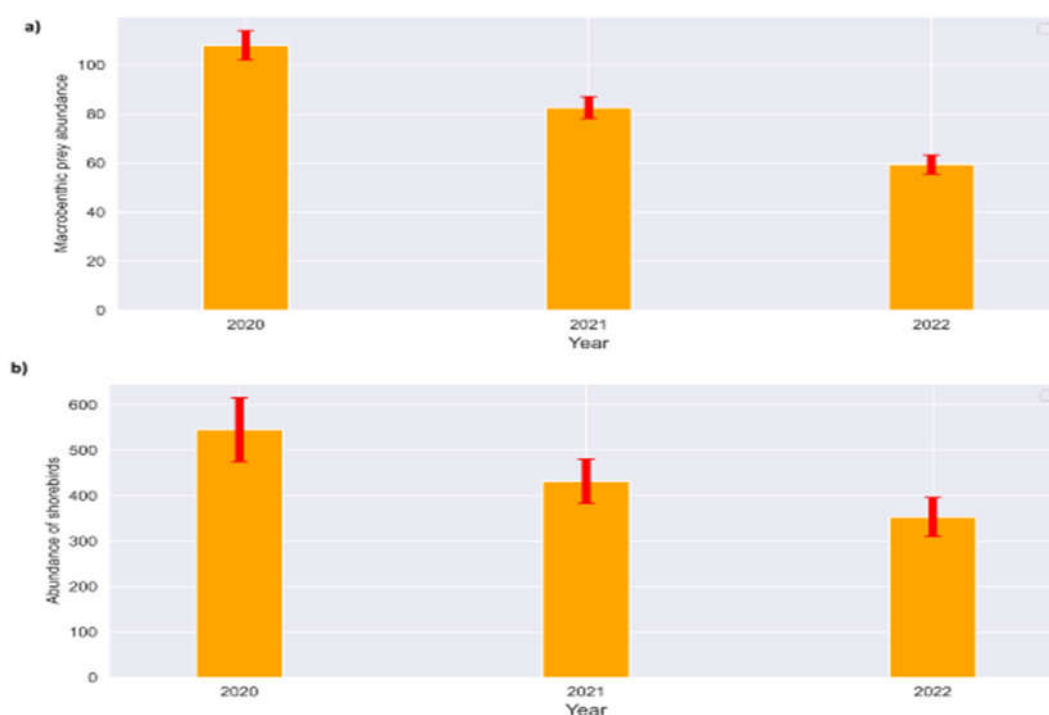


Figure 46. Abundance of benthic macroinvertebrate prey (a) and shorebirds (b), across the years between 2020-2022, in the entire study area.

Impact of microplastics in droppings on shorebird population

Shorebird droppings samples contained significant quantities of microplastics (Table 22), which increased over the years. The abundance of shorebirds across the study area displayed a steep decline over the years (Figure 46b). None of the models can statistically explain shorebird abundance in the studied regions, but some values are important to analyse. The values far from zero in the deviation of residuals were obtained, indicating that the data was not well predicted. The intercept value was 180.4 (p-value: 0.997), indicating that it was not significant. The microplastic coefficient (-0.001362, p-value: 0.006611) indicated a significant negative effect on the abundance of shorebirds (Figure 45c). The AIC value was high (748.11). Several factors (such as microplastic, year, certain prey species, and different habitats) have significant effects on abundance. Variables with negative effects, like microplastic (0.14%), season: Pre-monsoon (-11%), year (-8%), and site: mudflats (1%), indicate a decrease in the rate of abundance of shorebirds. The mean abundance of shorebirds and prey (all species combined) significantly

reduced over the years (Figure 46). A model was run to test the relationship between shorebird abundance and prey abundance in the study area but this was not supported due to the high AIC value.

Table 22. Abundance (mean and SD) (particles/g) of various types of microplastics (fibres, fragments and granules) obtained from the droppings samples of shorebirds employing different modes of foraging in the study area.

Species	Mode of foraging	Specialization	Fibres	Fragments	Granules
Tibetan Sand Plover	Epibenthic feeders	Benthic invertebrates in the upper sediment layer	8.6 ± 2.4	1.7 ± 1.2	1 ± 0.47
Greater Sand Plover			8.7 ± 2.49	6.3 ± 1.24	1.7 ± 1.2
Kentish Plover			0.7 ± 0.9	0	8.6 ± 2.49
Common Sandpiper			27.3 ± 12.4	6.3 ± 1.2	1.7 ± 1.2
Common Redshank	Epi-meso-faunal benthic and Pelagic feeders	Benthic invertebrates in upper, medium and depth sediment layers and water column. Zooplanktonic prey items via surface tension transport	48.3 ± 23.6	6.3 ± 1.2	22.6 ± 9.9
Common Greenshank			55.3 ± 27.4	8.7 ± 2.4	1.7 ± 1.2
Bar-tailed Godwit	Epi-meso-infaunal benthic feeders	Benthic invertebrates in upper, and medium and depth sediment layers.	53 ± 23.5	22.6 ± 9.9	13.3 ± 4.9
Whimbrel			39 ± 18.7	11 ± 3.7	1.7 ± 1.2
Eurasian Curlew			36.7 ± 17.4	13.3 ± 4.9	11 ± 3.7
Sanderling	Epibenthic & biofilm feeders	Benthic invertebrates in the upper sediment layer, Biofilm grazing.	13.3 ± 4.9	1.7 ± 1.2	6.4 ± 1.2

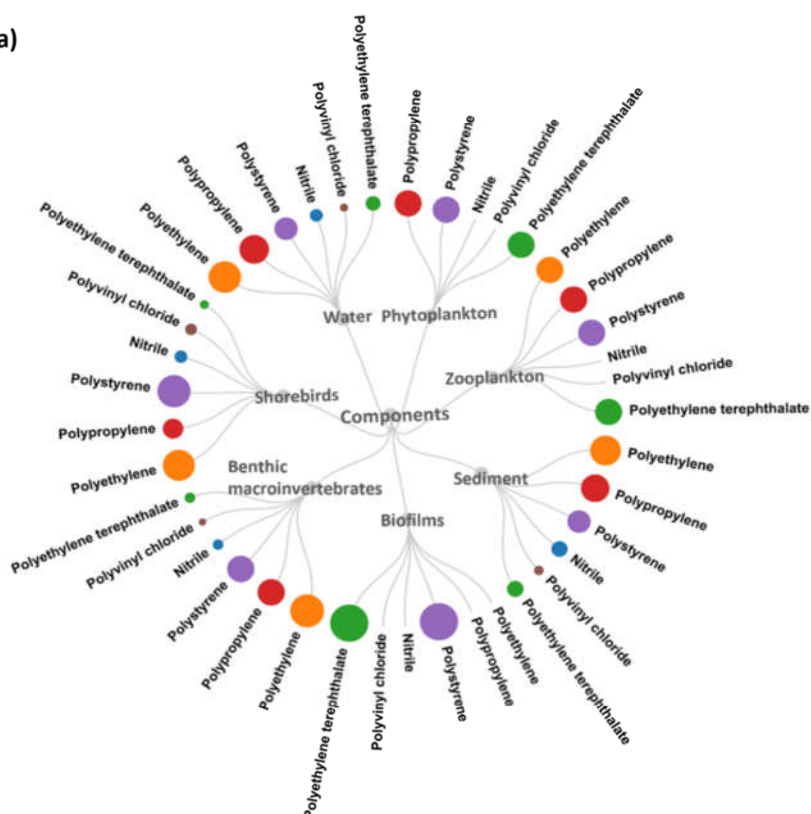
Types of microplastics in entire abiotic and biotic samples

The study identified three types of microplastics across the samples: fibres, fragments, and granules, with fibres showing most prevalence in water and sediment samples. Conversely, fragments were most abundant in biofilms followed by granules, with fibres being the least common. In phytoplankton, fragments were the dominant type, while fibres were most abundant in zooplankton. In benthic macroinvertebrate prey (all species combined) also, fibres were the most prevalent microplastic type (Table 20). Among shorebirds, the predominant types of microplastics were fibres. However, quantities varied significantly across species

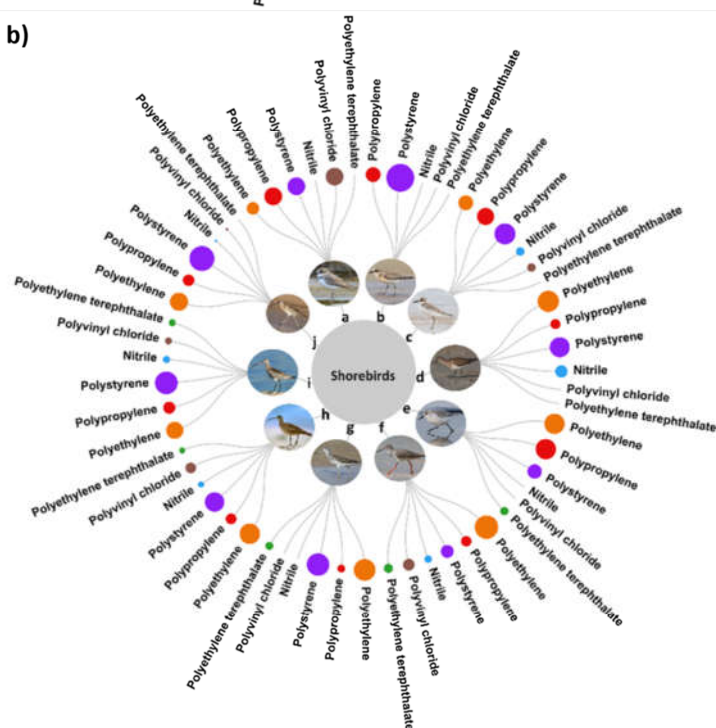
with different foraging strategies. Highest levels of all microplastic types were detected in shorebirds that forage through multiple sediment layers. The highest concentrations of microfibrils were detected in droppings samples of Common Greenshank, Bar-tailed Godwit, and Common Redshank (Table 22). The Bar-tailed Godwit's droppings exhibited the highest concentrations of fragments, while the Common Redshank's droppings contained the most granules. Lower quantities of all microplastic types were observed in exclusively epibenthic feeders. Despite this, the droppings of Common Sandpiper contained relatively higher quantities of fibrils and fragments. Among surface feeders, the Kentish Plover showed the lowest quantities of fibrils and fragments but the highest quantity of granules. Sanderlings, which graze on biofilms, showed higher levels of fibrils in their droppings compared to exclusively epibenthic plovers.

Analysis of microplastics isolated from biotic and abiotic samples revealed a diverse range of polymers including polyethylene, polypropylene, polystyrene, polyvinyl chloride, nitrile and polyethylene terephthalate. Polyethylene and polypropylene were predominant in water, sediment and benthic macroinvertebrate prey items consumed by the shorebirds. Microplastics identified in phytoplankton and zooplankton were composed of polyethylene, polypropylene, polystyrene and polyethylene terephthalate, while biofilm samples contain polyethylene terephthalate and polystyrene (Figure 47a). Polyethylene dominated the most in *Dottilla myctiroides*, *Ceratonereis burmensis* and *Heteromastus filiformis* samples while polypropylene dominated the most in *Metapenaeus dobsoni* and *Emerita holthuisi*. However, the polymer profile in shorebird droppings exhibited a diverged pattern, with polystyrene emerging abundantly, followed by polyethylene, polypropylene, polyvinyl chloride, nitrile, and polyethylene terephthalate (Figure 47b & 47c).

a)



b)



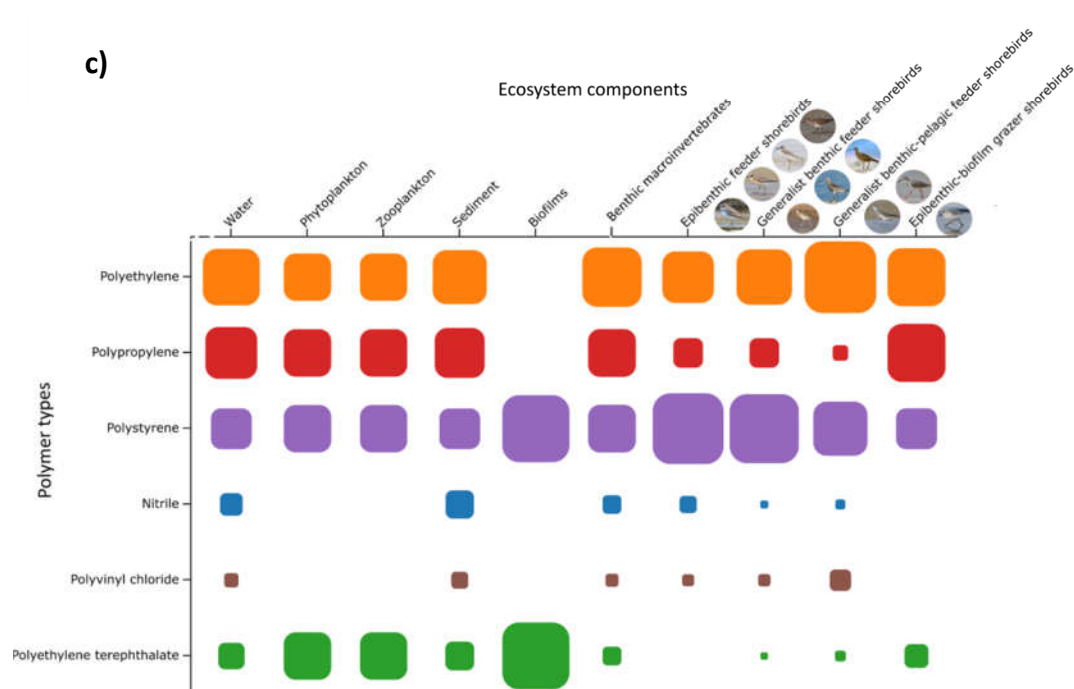


Figure 47: (a) The concentration and distribution of microplastic polymers across various ecosystem components; water, phytoplankton, zooplankton, sediment, biofilms, benthic macroinvertebrates and shorebirds. Bubble size represents the concentration (%) of each polymer, with the following colour-coded ranges: saffron (20-40), red (10-30), purple (10-50), cyan (0.1-10), brown (0.1-10), green (0.1-50). **(b)** The visual representation of concentration (%) and distribution of polymers in droppings samples from selected shorebird species. Species are identified as: (a) Kentish Plover, (b) Tibetan Sand Plover, (c) Greater Sand Plover, (d) Common Sandpiper, (e) Sanderling, (f) Common Redshank, (g) Common Greenshank, (h) Whimbrel, (i) Bar-tailed Godwit and (j) Eurasian Curlew. Bubble size represents the concentration (%) of each polymer, with the following colour-coded ranges: saffron (10-50), red (0.1-40), purple (10-70), cyan (0.1-20), brown (0.1-30), green (1-10). **(c)** The matrix illustrates the relationship between the microplastic polymer concentrations in shorebirds employing different foraging strategies and their corresponding abundance in other ecosystem components. Varying concentration (%) of the six polymer types are shown across water, phytoplankton, zooplankton, sediment, biofilms, benthic macroinvertebrates and four categorized group of the investigated shorebird species. The size of each rectangle represents polymer concentration with the following colour-coded ranges: saffron (20-60), red (1-40), purple (10-60), cyan (0.1-10), brown (1-10), green (0.1-30).

Discussion

Occurrence and distribution of microplastics

Microplastic pollution is a growing threat to aquatic ecosystems worldwide. The study documented significant microplastic concentrations across a range of samples, including water, sediment, biofilm, plankton, benthic macroinvertebrates,

and shorebird droppings from ten intertidal habitats along the western coastline of India, collected between 2020 and 2022.

Based on the results of network analysis, water has been identified as the main pathway by which microplastics enter the other ecosystem compartments (Figure 36). Earlier studies also indicated that riverine inputs are the most significant source for marine plastic debris (Rech et al., 2014; Zhao et al., 2015). Anthropogenic activities and riverine microplastic transport are the major source of microplastics in the coastal waters in west coast of India and this can be attributed to the microplastic contamination at KVCR mudflat, KVCR mangroves, Korappuzha beach, Elathur beach, Iringal estuary and Kolavippalam beach, as they are located at the mouth of three major rivers namely Kadalundi river, Korappuzha river and Kuttiady river, while the other beaches are situated in the vicinity. The most produced and buoyant type PE and PP microplastics dominated in water samples.

Along with that, PCA revealed the predominance of large sized (0.3-0.4 mm) microplastic particles in the water samples whereas the sediment samples were abundantly enriched with smaller sized particles (Figure 38). This, in turn, points towards microplastic settlement and fragmentation in the sediments. According to earlier research (Klein et al., 2015; Lin et al., 2018; Rodrigues et al., 2018), particle density can be increased by weathering and biofouling, adding materials during production, forming hetero-aggregates, or sorbing biomolecules (Chubarenko et al., 2016; Corcoran, 2015; Mor'et-Ferguson et al., 2010). Fouling communities of microbes colonizes over plastics forming biofilms and play key role in the degradation, sinking and depositing of plastic particles over sediments (Zettler et al., 2013; Kaiser et al., 2017). Since the west coast of India has already been reported to be polluted by discarded fishing gears and debris from developmental activities (Aarif et al., 2014, 2021b), plastic particles accumulate for a long time in the study area and are entrapped in the sediments, increasing the density of microplastics in sediment samples.

Microplastics were observed in all the prey samples collected from the study area. The feeding behaviour and life cycle of this sediment-dwelling worms might have contributed to this (Knutsen et al., 2020). The size range of the sediment settled microplastics makes them available for the small-sized, deposit and suspension feeders in particular (Van Cauwenberghe et al., 2015).

All the droppings collected from 10 different species of shorebirds were found to have different types of microplastic particles. The network analysis showed that these particles were spread from the abiotic factors such as water and sediments and also through the food chain from their primary prey items (Figure 37). The foraging strategy influences the ingestion and retention level of microplastics (Liu et al., 2023). Species that feed at the water surface or convergent zones, where plastic pollution accumulates in the environment (Ryan, 2016; Roman et al., 2019), appear to be more susceptible (Poon et al., 2017; Baak et al., 2020). Surface foraging birds are highly vulnerable to microplastic pollution since they may mistake the microplastic contents as prey, while concentrating food from larger volumes of water (Sfriso et al., 2020). Comparatively higher quantities of microplastics were observed, in the droppings of Common Greenshank and Common Redshank, which were previously reported as feeding on intertidal invertebrates at or near the sediment surface and in shallow water column (Mishra et al., 2019; Choi et al., 2021). Medium sized shorebirds were already observed as ingesting microplastics (Moser & Lee 2006), due to their peculiar mechanism of prey transport known as surface tension transport to ingest small planktonic prey items from the water surface (Rubega, 1997). Common Redshank was observed as employing this mechanism in their natural habitat (Estrella et al., 2007). The findings are consistent with the previous study confirming the role of foraging strategy of shorebirds in the ingestion rate of microplastics, where surface foraging shorebird droppings contained 32 X more plastic particles than the deep foraging one (Mylius et al., 2023).

Besides primary ingestion of plastics as noted above, shorebirds may also accumulate plastics through secondary ingestion (Hipfner et al., 2018; Provencher et al., 2019). Microplastics were observed in all the prey samples collected during the present study, which makes them more bioavailable to shorebirds, the top-level predators in the coastal ecosystems. The PCA demonstrates that *Ceratonereis burmensis* contributed more microplastics for shorebirds to consume (Figure 39). This can be attributed to high abundance of this polychaete species and the preference of shorebirds to them. Additionally, their opportunistic behaviour of using both deposit feeding and filter feeding (Quadros et al., 2009) may have contributed to the high levels of microplastics in *Ceratonereis burmensis*. However, more studies need to be carried out to understand the role of the pollutant elimination rate of this species. The microplastic contamination might cause community changes in prey organisms, resulting in diversity shifts among shorebirds as observed by Shamna et al. (2023).

The study observed comparatively larger fragments (2.22-4.30 mm) in the droppings of Bar-tailed Godwit and Whimbrel, that usually prey upon buried macroinvertebrates in intertidal zones, which makes them more vulnerable to the ingestion of microplastics from the sediments as well (Mylius et al., 2023). The PCA also showed that the microplastics ingested by Bar-tailed Godwits were mostly of the size range 0.3-0.4 mm (Figure 38), which was the size range mostly occurred in the water samples. This can be attributed to the larger size and generalist foraging behaviour of Bar-tailed Godwits (dit Durell, 2007). Their behaviour of ingesting prey along with water to avoid friction also leads to additional ingestion of larger microplastic particles in the water column.

It was observed that an increased consumption of microplastics by birds has been linked to an increase in pathogens and plastic degrading microbes, as well as a decrease in commensal gut microbiota (Fackelmann et al., 2023). Therefore, more research to understand the microbiota of wintering shorebirds in the study area will shed light on the rate of ingestion of microplastic and its impacts on them.

Microplastics can cause lethal or sublethal effects in avian fauna when ingested (Bearzi et al., 2022) and further, the absorption of xenobiotics facilitated by biofilms and its biomagnification can cause biological and ecological consequences, including internal physical and chemical damages (Vecchi et al., 2021). Microplastics are instrumental in the absorption and transfer of diverse toxic contaminants such as organic compounds, heavy metals and antibiotics in the surrounding environment and along the food webs (Cao et al., 2021). Aarif et al. (2023) substantiated the trophic transfer of heavy metals, demonstrating elevated concentrations in shorebird droppings, prey, and sediment samples taken from the KVCR mudflats, mangroves and adjoining sand beaches. Further investigation into the correlation between microplastics contamination and the concentration of heavy metals across diverse trophic levels and habitats is warranted, particularly in light of the alarming decline in hydrological and substrate qualities, as emphasized by Rubeena et al. (2023). The accumulation of toxic contaminants in the biotic and abiotic components of the ecosystem can induce various impacts on shorebirds such as delay in the departure, consequently contributing to their population decline (Aarif et al., 2021a).

Co-occurrence of heavy metals and microplastics in shorebird droppings

The current study reported high concentrations of heavy metals, including Zn, Cu, Co, Cr, Pb, and Cd, along with substantial amounts of PE, PP, PS, PVC, nitrile and PET microplastics in ten commonly observed migrant shorebirds in the study area (Table 18). These pollutants can be ingested directly from the contaminated environment or indirectly through the food chain, with shorebirds acting as apex predators in coastal ecosystems (Figure 48). The findings highlight significant concentration of heavy metals excreted by shorebirds. This is indicating that they are exposed to high levels of various heavy metals from sources close to their wintering areas (Aarif et al., 2023). Among the observed heavy metals, Cr, Pb, and Cd are highly toxic even in low concentrations (Rahman & Singh, 2019). In higher concentrations, all heavy metals have the potential to exert a detrimental effect on shorebirds and cause a decline in their population (Ma et al., 2022).

Distinct patterns of heavy metal concentrations were observed across shorebird species (Figure 40). Aarif et al. (2023), reported significantly higher concentrations of Zn, Cu and Co in sediment and prey organisms in sandy beaches compared to mudflats and mangroves. In line with this, Zn and Cu were more abundant in droppings collected from sand beaches compared to mudflats and mangroves, except in Kentish Plover. Kentish Plover in mudflats and mangroves had higher concentrations of both heavy metals, while those in sand beaches had lower concentrations. Eurasian Curlew exhibited very high and almost similar concentrations of Zn in mudflats, mangroves and sand beaches. Co concentrations were consistent with those previously reported in sediment and prey organisms in each habitat (Aarif et al., 2023). The exceptionally low concentrations of all three non-hazardous heavy metals in Bar-tailed Godwit across all three habitats studied were found to be of particular interest.

Cr was detected at high levels in all shorebird species, with concentrations ranging from 20.40 ± 8.48 – 86.84 ± 0.58 mg/kg. Eurasian Curlew exhibited the highest Cr concentrations, though similarly elevated levels were also observed in smaller shorebird species (Table 18). This aligns with the previously reported high Cr concentrations found in sediments and invertebrates, particularly from sand beaches (Aarif et al., 2023). The significant levels of Cr in sanderling droppings from sand beaches were comparable to those of the Eurasian Curlew (Figure 40). However, some species, such as Tibetan Sand Plover, Greater Sand Plover, Common Greenshank and whimbrel had lower Cr levels in sand beaches compared to mudflats and mangroves. Given the different size ranges and ecological niches that the involved species represent, this discrepancy deserves more research. Despite lower non-hazardous heavy metal concentration in Bar-tailed Godwits, Cr levels were notably high across all habitats. These elevated Cr levels suggest significant dietary exposure, as Cr in droppings reflects contamination from food sources (Eeva et al., 2020). This is consistent with the finding that the primary source of Cr exposure for wild birds is through food consumption (Outridge & Scheuhammer,

1993). Elevated Cr levels can adversely affect avian DNA, protein function and migration (Morales et al., 2016; Pandiyan et al., 2022).

Pb, even in the low concentrations, can adversely affect avian physiology, including feeding behaviour, thermoregulation, brain development and reproductive success, which can have serious consequences for their populations (Burger & Gochfeld, 2000). Aarif et al. (2023), found lowest Pb levels in sediments from sand beaches than mudflats and mangroves, whereas sand beaches showed prey hosting highest Pb concentration. This may be ascribed to the enhanced bioavailability of Pb linked with the heavy mineral concentrate (Zhang et al., 2014), which is prevalent in sandy sediments (Sharath Raj et al., 2022). This observation aligns with previous studies demonstrating the influence of mineral associations on Pb bioavailability (De La Peña-Lastra et al., 2022). Notably, Pb levels were higher in the droppings of Bar-tailed Godwit across all the habitats, suggesting significant exposure through contaminated prey.

Similarly, Cd exhibited the lowest concentrations in sediments and the highest in macrobenthic prey from sand beaches (Aarif et al., 2023). Elevated levels of Cd in mangrove sediments and shorebird droppings from sand beaches and mangroves indicating uptake through sediment ingestion and consumption of contaminated prey. Contrary to the general trend, Eurasian Curlews exhibited elevated Cd levels in their droppings samples collected from mudflats. This observation may be explained by their preference for larger prey items and increased consumption in estuarine mudflats (Li et al., 2020). In Bar-tailed Godwits, Cd levels were consistent across mudflats, mangroves and sand beaches. Chronic exposure to Cd can lead to a cascade of adverse effects in birds, including impaired haemoglobin synthesis, stunted growth, renal dysfunction, reproductive impairment, and endocrine issues (Shi et al., 2017).

Microplastic ingestion has been associated with several harmful effects in shorebirds, such as reduced feeding, reproductive failure, endocrine disruption and

even mortality (Jovanovic, 2017). The current study identified significant concentrations of various polymer types in the droppings of all the shorebirds considered. According to Robin et al. (2020), PE was found to be the most representative polymer types in coastal waters of southwest India and the current findings are consistent with those. PE was found to be most common in opportunistic planktivorous shorebirds such as Common Greenshank and Common Redshank, likely due to the surface tension prey transport. Furthermore, PS was prevalent across all shorebird droppings samples (Figure 43), highlights its widespread environmental presence and its propensity to accumulate further up the food chain (Kik et al., 2020). This suggests that shorebirds at KVCR may be experiencing indirect microplastic exposure via the food chain, contributing to the overall decline in shorebird populations along India's west coast.

Analysis of shorebird droppings revealed a significant co-occurrence of microplastics with the potentially harmful heavy metal Cr, with the highest rates observed in near-threatened species (Figure 44). This is challenging since, Kim et al. (2022), observed that the PS microplastics can exacerbate Cr toxicity, even at environmental levels. In this study, Cr was the most abundant metal in Common Redshank and Common Greenshank, both of which had high levels of PE. This is consistent with the finding of Robin et al. (2020), that PE materials harbour high Cr concentrations in coastal waters of southwest India. Given the frequency of these contaminants in shorebirds, urgent measures to reduce contamination in the habitats are required. The high affinity of microplastics for heavy metals, increases the bioavailability and toxicity of both contaminants, posing serious risk to the health of shorebird populations (Campanale et al., 2020).

It was discovered that some environmental factors directly causing the population decline and the delayed departure of shorebirds from the west coast, including changes in relative humidity, rainfall, water temperature, air temperature, salinity, and the abundance of invertebrate prey (Aarif et al., 2021a). These climate change stressors were also reported to have interactive effects on pollutant mobilisation,

bioaccumulation and enhanced toxicity in estuarine and marine biota (Greco et al., 2011; Pawar et al., 2020; Kibria et al., 2021).

The present study reveals comparatively higher concentrations of heavy metals in shorebird droppings from the west coast, than the heavy metal concentrations previously reported in shorebird feathers from the east coast (Pandiyan et al., 2020). Given the fact that the droppings analysis for pollutants give insights into the contamination level of shorebirds' foraging habitats (Rutkowska et al., 2018), current findings reveals that the foraging grounds on the west coast are severely contaminated. This suggests that the pollution in the foraging habitats on the west coast may be one of the main causes for the decline in migratory shorebirds population, despite the higher productivity of west coast (Rashiba et al., 2022). Further, heavy metals and microplastics are considered as the most worrisome environmental pollutants, because of their potential to induce harmful effects on ecosystems and human health. The presence of these pollutants in combination poses a heightened risk, potentially resulting in undesirable synergistic consequences. Hence, the present study is highly significant in conservation perspective, as it reports high concentrations of hazardous and non-hazardous heavy metals (including Zn, Cu, Co, Cr, Pb, and Cd) alongside significant quantities of PE, PP, PS, PVC, nitrile and PET in droppings of all ten shorebirds studied. Given the complex dynamics between microplastics, heavy metals, and climate change, further research is imperative to determine their combined impact on coastal ecosystems and its components. Addressing these multifaceted environmental challenges is critical to conserve biodiversity and mitigating the catastrophic decline of migratory shorebird populations.

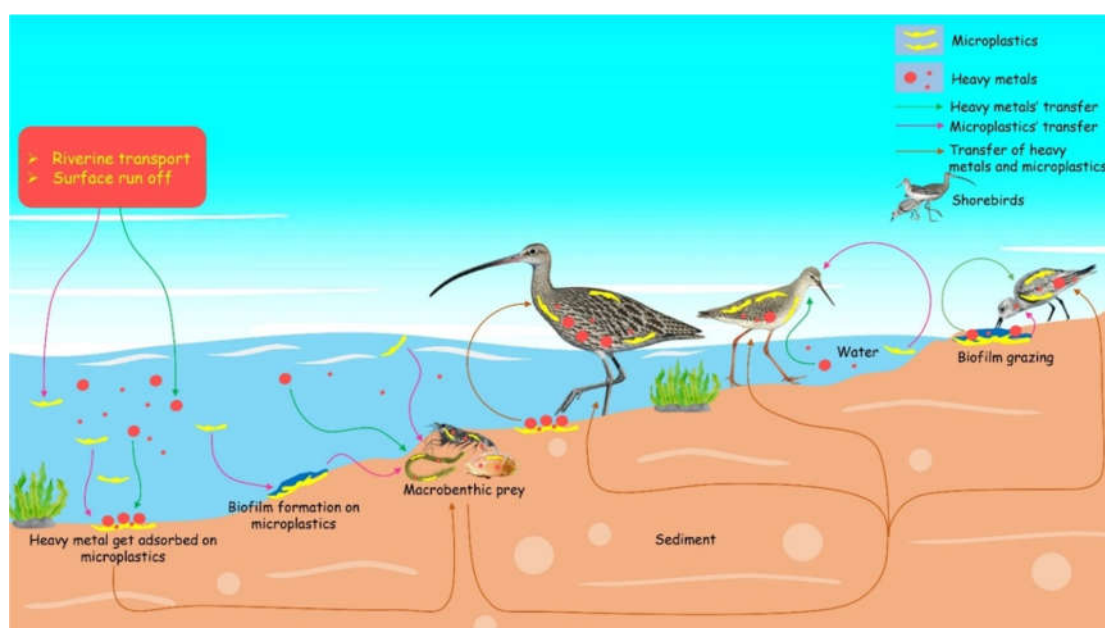


Figure 48. The hypothesized routes of microplastic and heavy metal ingestion by shorebirds; direct contact with polluted environments and indirect uptake via contaminated prey.

Temporal and spatial variability of microplastic abundance in environmental samples

The spatial patterns of microplastics in water and sediment demonstrated significant variability across different habitats, with the highest concentrations observed in mangroves followed by mudflats, and the lowest in sand beaches (Figure 49). This spatial variability highlights the influence of habitat characteristics on microplastic accumulation. The KVCR mangroves situated in the upper estuary and proximate to human settlements, are exposed to direct waste dumping and debris carried by the river. The entangled aerial root systems of mangroves are known to effectively capture and accumulate larger plastic debris transported by rivers and surface runoff (van Bijsterveldt et al., 2021). This mechanism prevents immediate downstream transport to other near shore habitats such as mudflats and sand beaches. Marine plastic debris brought by waves and currents also becomes entrapped in mangrove ecosystems, as aerial roots reduce water flow (Deng et al., 2021). Within KVCR estuary, an uncontrolled proliferation of mangroves has been documented (Aarif & Musammilu, 2018), and their dense

vegetation further enhances debris retention (Ivar do Sul et al., 2014), promoting the gradual breakdown of plastic waste into microplastics over time.

Therefore, the proximity of mangroves to terrestrial sources, coupled with their exceptional capacity to trap debris from rivers, runoff, and seawater during high tides (Deng et al., 2021), significantly contributes to elevated microplastic levels in mangrove waters. These microplastics undergo sedimentation and suspension, along with the surface sediments (Liu et al., 2022). The low-energy environment of mangroves is ideal for the deposition of fine particles, including microplastics (Kuwaie et al., 2021), leading to increased microplastic concentration in mangrove sediments. Zhang et al. (2024) observed that the abundance of microplastics in mangrove habitats was approximately 1.6 times higher compared to non-mangrove environments, underscoring the interception effect of these ecosystems on microplastics. Mudflats, although exposed to similar sources of plastic debris, exhibit slightly lower microplastic abundance due to their open habitat nature (Lo et al., 2018). However, compared to high-energy environments such as sand beaches, mudflats within estuaries are still more favourable for microplastic deposition (Lo et al., 2018). Studies in various ecosystems, including estuaries, have shown a correlation between decreasing sediment grain size and increasing microplastic concentrations (Ling et al., 2017; Vermeiren et al., 2021). This suggests that finer sediments, like those found in mudflats and mangroves, have a greater capacity to trap and retain microplastics. Sandy shorelines, while accumulating microplastics through tidal processes, have a dynamic nature that limits their retention in the water column (Nhon et al., 2022). Within sand beaches, microplastic abundance in the water column was highest at Pulimudu beach and in sediment at Thikkodi beach and Pulimudu beach (Table 19). This trend suggests a clear link between anthropogenic influence and microplastic abundance within a habitat. The current investigation revealed that beaches with higher levels of human activity, such as tourist destinations and harbours, exhibited higher microplastic concentrations in both water and sediments. Pulimudu beach,

adjacent to Beypore fishing harbour and Thikkodi beach, a drive-in beach subject to significant anthropogenic pressure. Conversely, the lowest abundance of microplastics was reported from Kappad beach and Elathur beach. Kappad beach, while a tourist spot, is a well-maintained historic area with minimal human impact on the coast (Athira et al., 2024a). Similarly, Elathur beach, is less populated and is not featured on tourist maps, reflecting the influence of human activity on microplastic levels.

Significant annual variation in microplastic abundance was observed, with the lowest levels in 2021 and the highest in 2022. This decrease in 2021 may be attributed to reduced anthropogenic activity and decreased single-use plastic consumption during the COVID-19 pandemic. Successive lockdowns likely contributed to lower microplastic levels in surface waters and freshly deposited sediments along the west coast. This hypothesis is supported by recent studies along the Goa coast (west coast of India), which documented a sharp, two to sevenfold decrease in microplastic concentrations during the post-pandemic year 2021 (Nigam et al., 2022; Gupta et al., 2024). The sharp increase in 2022 further reinforces the link between anthropogenic activity and microplastic abundance. A seasonal trend was also observed in microplastic abundance, with peak levels during the monsoon season. This trend is likely due to surface runoff from surrounding areas, and the resuspension of previously settled microplastics due to increased water flow (Talbot & Chang, 2022). These findings align with studies conducted along the west Coast (Maurya et al., 2024; Mukhopadhyay & Mukhopadhyay, 2024), which consistently show heightened microplastic abundance during the monsoon season.

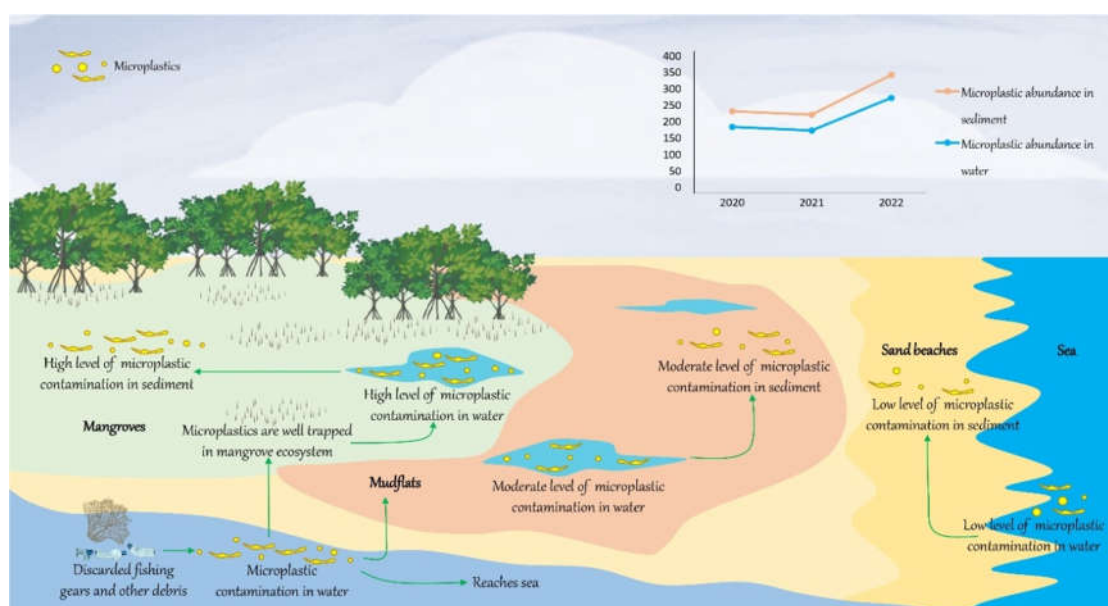


Figure 49. Demonstrating the varying abundance of microplastics in water and sediment, across different habitats (mudflats, mangroves and sand beaches). The accompanying graph depicts temporal variations in microplastic levels over the study period, along the west coast of India.

Trophic transfer of microplastics in coastal foodweb and its impact on shorebirds

Intertidal habitats comprise a complex network of interconnected systems, where biological communities interact with their physical environment (Gauzens et al., 2020). Intertidal biofilms, composed of microbes, their extracellular mucus substances, and detritus are an inevitable component of the coastal food web. They are consumed by a range of estuarine taxa, including invertebrates (Herman et al., 2000) and certain shorebirds (Kuwaie et al., 2008; Mathot et al., 2018). Biofilm formation can lead to partial degradation of microplastics and the release of harmful leachates and toxins (Cole et al., 2019), thereby increasing bioavailability of microplastics and any co-contaminants they may absorb (Rochman et al., 2013). Therefore, the adherence to biofilm on microplastics can influence the behaviours and potential risks of microplastics to the organisms consuming the biofilms (Corami et al., 2022). Phytoplankton, key primary producers in the marine environment, along with zooplankton were also found to contain microplastics. These tiny plastic particles interact with phytoplankton by adherence to their surface and reach zooplankton via ingestion from surrounding sources (Huang et al., 2020). An increasing trend in microplastic concentration was observed over the

years. The study noted a higher abundance of microplastics in zooplankton compared to phytoplankton, suggesting trophic accumulation. Impaired photosynthesis (Wu et al., 2019), altered chlorophyll content (Zhang et al., 2017), changes in gene expression (Zhou et al., 2021), increased oxidative stress (Fu et al., 2019), and variations in nutrient availability (Chen et al., 2020) are some of the documented impacts of microplastics on phytoplankton. The ingestion of microplastics also has adverse effects on zooplankton affecting their growth rates, cell viability (Gomes et al., 2020), and fecundity (Cole et al., 2015).

The presence of microplastics in organisms at higher trophic levels including invertebrates and shorebirds are an emerging concern with poorly understood consequences. Aarif et al. (2021a) previously reported a steep decline in benthic macroinvertebrate fauna, major prey items for shorebirds, between 2010 and 2019 along the west coast. This decline was primarily explained by increased salinity and alterations in water and sediment quality. The current study, however, is the first to investigate the potential impact of microplastics on this decline. The presence of microplastics was detected in all samples of benthic macroinvertebrates, with concentrations increasing over time. The life cycle and filter feeding or deposit feeding behaviour of these organisms might have contributed to this trend (Quadros et al., 2009). Microplastics can reach them either through water, sediment or planktonic prey items (Athira et al., 2024a). Additionally, a parallel reduction in the abundance of these invertebrates was observed throughout the study period. Despite these observations, statistical analysis did not reveal a significant direct effect of microplastic concentration on prey abundance. Nevertheless, the substantial and increasing mean abundance of microplastics in macrobenthos suggests a potential vulnerability, raising concerns about future impacts.

A significant decline in shorebird abundance was documented, correlating with the observed depletion of their benthic macroinvertebrate prey. However, the current study failed to establish a direct cause-and-effect relationship between prey abundance and shorebird abundance. In contrast, a significant negative effect of microplastic abundance on shorebird populations was identified. Although there is

no direct evidence linking microplastics to mortality in shorebirds, their accumulation in the digestive tract can reduce the available space for food items and impair digestive efficiency (Rossi et al., 2019). Additionally, microplastics can adsorb heavy metals from the environment, increasing the bioavailability of these metals (Khalid et al., 2021). The bioaccumulation of heavy metals is known to pose several health risks to avian species and contributes to population declines (Kitowski et al., 2017). Previous studies along the west coast of India have documented high levels of heavy metals in shorebird droppings and their association with specific polymer types (Aarif et al., 2023, 2024; Athira et al., 2024b). Therefore, further research is crucial to elucidate the ecological and toxicological risks associated with microplastic accumulation and their potential impact on shorebird populations.

The fate and transport of microplastics in coastal ecosystems are greatly determined by their physical properties. The study identifies three primary types of microplastics: fibres, fragments, and granules. Fibres constituted the exceptionally dominant microplastic particle shape in both sediment and water samples. According to Wu et al. (2022), the form of microplastics is indicative of their sources and degradation processes. The predominance of fibres suggests that the main source of microplastic particles in the study area may be various types of discarded commercial fishing gear and domestic sewage. This inference is supported by Aarif et al. (2021b), who documented the prevalence of plastic debris especially from discarded fishing gear along the west coast, leading to entanglement and injuries in migratory shorebirds. The consistent presence of fibres across different environmental matrices underscores their persistence and widespread distribution in coastal ecosystems. While fibres dominated water and sediment samples, fragments and granules were significantly abundant in biofilms. The larger surface area to volume ratio of fragments and granules provides more opportunities for various microbial colonization and biofilm formation (Nath et al., 2023). Conversely, plankton and benthic macroinvertebrate samples exhibited a higher abundance of fibres. The buoyancy allows fibres to remain suspended in the water column longer (Issac & Kandasubramanian, 2021), increasing their exposure

to pelagic organisms and filter-feeding macrobenthos. Despite their suspension-feeding behaviour, *Cosmonotus* crabs collected from sand beaches contained lower quantities of microplastics compared to prey samples from the KVCR estuarine mudflats. This difference may be due to the generally lower levels of microplastics observed in sand beach environments or potentially reduced bioavailability due to minimal biofilm formation on microplastics in these areas. Further investigations are necessary to elucidate the variations observed in microplastic ingestion and accumulation by different benthic macroinvertebrate species. The overall abundance of microplastics in shorebirds (all species combined) followed the trend of fibres dominating over fragments and granules. Variations in microplastic types ingested were linked to their varying foraging strategies (Figure 50). Species foraging through multiple sediment layers (generalists), exhibited higher levels of all microplastic types. This may be attributed to their broad diets and extensive foraging areas, which often include the water column (Provencher et al., 2010). Bar-tailed Godwit, noted for washing their prey in shallow water or ingesting water alongside food to ease passage through their straight beak (Athira et al., 2024c), may experience increased microplastic exposure. Similarly, the Common Redshank and Common Greenshank, with their planktivorous diet, are likely to ingest microplastics mistaken for natural prey (Savoca et al., 2017). This is further supported by the higher concentrations of microfibrils found in their droppings (Table 22), mirroring the microplastic composition observed in water, sediment, and plankton samples. Additionally, other multiple sediment layer feeders like the Eurasian Curlew and Whimbrel, also contain microplastics in their droppings, though in lower quantities.

Epibenthic feeders, with a more limited foraging range, generally displayed the lowest levels of microplastics. Sanderlings, which graze on biofilms, were noted to have higher levels of fibres in their droppings compared to exclusively epibenthic feeders. The sweeping motion employed while biofilm grazing (Kuwaie et al., 2008), likely increases their chance of accidentally obtaining microplastics than species pecking food after visual detection. This finding underscores the role of biofilms as reservoirs for microplastics and their subsequent transfer to shorebirds. The

disparity in microplastic types and quantities among shorebirds with different feeding strategies highlights the complex interactions between microplastic pollution, prey availability, and foraging behaviour in coastal ecosystems. Athira et al. (2024a) reported a correlation between foraging behaviour and ingested microplastic polymer types in shorebirds. They identified a heightened vulnerability for opportunistic feeders to ingest polymers predominantly dispersed in the water column. Similarly, the present study revealed a diverse range of polymers within the microplastics isolated from all analysed samples. Interestingly, polystyrene emerged as the dominant polymer in shorebirds. This finding is particularly concerning as polystyrene has been linked to enhanced toxicity of various xenobiotics (Kim et al., 2022).

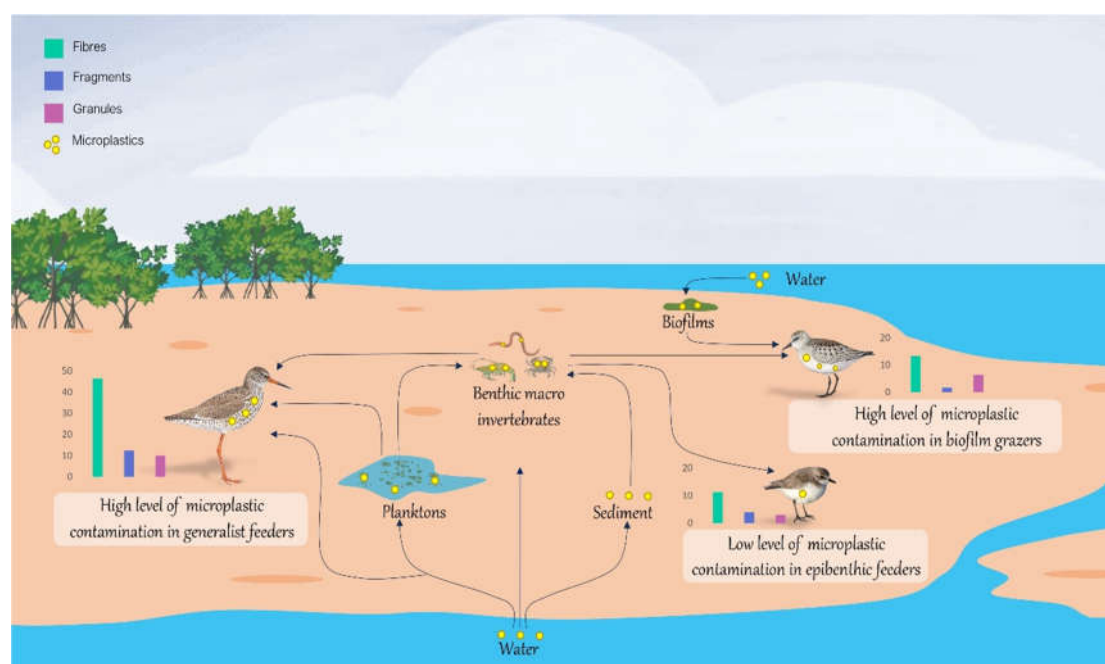


Figure 50. Demonstrating the transfer of microplastics through coastal food web and the varying abundance of different microplastic types (fibres, fragments and granules), in shorebirds employing different foraging techniques.

This study contributes to our understanding of the factors affecting shorebirds along India's west coast, in line with previous research on population declines (Aarif et al., 2014; Aarif & Musammilu, 2018), delayed departures (Aarif et al., 2021a), and recent habitat shifts (Byju et al., 2024). Microplastic ingestion poses a threat to the health and survival of shorebirds feeding in coastal habitats. Once

ingested, microplastic particles have been detected in various tissues, including skin, muscle and bloodstream, beyond the digestive tract (Allen et al., 2022). Research suggests that ingestion of these particles can lead to both acute and chronic health effects in bird species (Bearzi et al., 2022), including internal physical or chemical damages (Vecchi et al., 2021). The observed spatial, annual, and seasonal variations in microplastic abundance highlight the urgent need for stricter conservation strategies, particularly in the critically important and fragile habitats utilized by migratory shorebirds. These strategies should prioritize mitigating microplastic pollution at its source to safeguard shorebird populations. Public awareness campaigns coupled with stricter regulations on plastic use and disposal are crucial steps towards achieving this goal. By implementing these recommendations and continuing research efforts, we can gain a deeper understanding of the ecological implications of microplastic pollution and develop effective mitigation strategies to protect coastal ecosystems and the vital shorebird populations that rely on them.

These findings underscore the urgent need for stricter regulations and improved waste management practices, particularly in coastal regions near river systems. Extended producer responsibility and stricter enforcement of existing rules should be prioritized. On a broader scale, international cooperation is crucial since the migratory species, cross multiple geopolitical boundaries. Collaborative actions among nations, particularly those sharing CAF are essential to harmonize pollution control policies. Additionally, further research is essential to understand the long-term consequences of microplastic exposure on various shorebird species and to develop effective conservation strategies for these vital ecosystems.



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Baseline



The threat of microplastics: Exploring pollution in coastal ecosystems and migratory shorebirds along the west coast of India

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ABSTRACT

To evaluate the exposure risk and ingestion of microplastics by migratory shorebirds, which are regarded as apex predators in the coastal ecosystem, this study investigated the ubiquitous presence of microplastics in estuarine and coastal habitats and their potential to be transferred in the food chains. We analysed the presence of microplastics in water, sediment, major macroinvertebrate prey and the guano samples of ten shorebird species from ten important wintering grounds in the west coast of India. Our results revealed that water is the primary source through which microplastics disseminate into various ecosystem components. Microplastic debris in various forms were reported in all samples analysed, with microfibrils being the most abundant form. While polyethylene and polypropylene were found as the major microplastic types in water, sediment, and prey samples, polystyrene was most abundant in guano samples. Microplastic transfer and impacts in this delicate ecosystem demand further investigations.

Microplastics are commonly referred to plastic particles with a size smaller than 5 mm. They can be formed by the disintegration of larger plastics (Law and Thompson, 2014) or that are manufactured by industrialists for use in cosmetics or personal care products (Crawford and Quinn, 2017). Microplastic contamination has been identified as a global issue but its mechanisms of action in triggering troubles in ecosystem structure and function have not yet been completely unravelled. Microplastic particles can reach a wide range of organisms by entering the food chain because they are found in all marine ecosystems, including sandy beaches, the coastal zone, the open ocean, and the deep sea (Carvalho Ferreira and Lôbo-Hajdu, 2023).

Being the apex predators in the coastal ecosystem, shorebirds have a high potential to be exposed to and ingest microplastics but have largely been overlooked in plastic pollution research. The majority of the shorebird species are long-distance, trans-oceanic migrants (Butler et al.,

2001) and their populations are declining at a faster rate than those of the resident species (Koleček et al., 2021). This suggests that the factors linked to migration are the proximate drivers of their plunge in numbers globally (Studds et al., 2017; Aarif et al., 2021a). Further, the populations of wintering shorebirds on the Indian coasts and wetlands that fall under the Central Asian Flyway (CAF) are reported to have plummeted in the last few decades (Aarif et al., 2021a; Agoramoorthy and Pandiyan, 2016; Rashiba et al., 2022; Rao et al., 2022). The loss and degradation of wintering and stop-over habitats contributed to this trend along the west coast of India (Aarif et al., 2014; Aarif and Musammilu, 2018). Alterations in environmental variables due to climate change and anthropogenic influence as well as concomitant invertebrate prey depletion, were found to be the major reasons behind the steep decline and delay in departure of shorebirds from these crucial wintering habitats (Aarif et al., 2011, 2021a; Rubeena et al., 2023).

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Baseline

Shorebird droppings analysis: Microplastics and heavy metals in a key conservation reserve and adjoining sand beaches in the west coast of India

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ABSTRACT

Coastlines are susceptible to plastic and heavy metal pollution, which can accumulate from both marine and terrestrial sources. Shorebirds, top-level predators in these fragile ecosystems are considered as indicators of environmental health. Here, we tested the occurrence of microplastics and heavy metals in the droppings of ten regular wintering migrant shorebird species in Kadalundi-Vallikkunnu Community Reserve and adjoining sand beaches during November, December and January, each year, between 2019 and 2021. Heavy metals were analysed by Flame Atomic Absorption Spectrophotometer and the microplastic polymer compositions were identified using ATR-FTIR spectroscopy. We detected high concentrations of heavy metals such as Zinc, Copper, Cobalt, Chromium, Lead and Cadmium in droppings. Polyethylene, Polypropylene, Polystyrene, Poly Vinyl Chloride, Nitrile and Polyethylene terephthalate were the polymers identified. Polystyrene (42.6 %) and chromium (ranges between 7.83 and 88.45 mg/kg) were found to be the most abundant contaminants in most of the species.

Environmental pollution disrupts the earth's living and non-living components, impairing ideal environmental processes (Suzuki et al., 2020). Pollutants cause primary damage, which is measurable and secondary damage, which affects biological food webs, and is evident only over prolonged durations (Yadav et al., 2022). Coastal pollution rates are twice as prevalent as that of inland pollution (Santhaseelan et al., 2021). Heavy metals and microplastics are the most concerning pollutants due to their potential to cause harmful effects on ecosystems and human health (Iyer et al., 2023). The discarded plastics in coastal areas can directly harm the organisms through entanglement and injury (Aarif et al., 2021b). The degradation and fragmentation of larger plastics into microplastics (<5 mm), which are ingested by various organisms, transferred through the food web, and get bioaccumulated (Ziani et al., 2023). Heavy metals known for their toxicity, persistence, and accumulative behaviours, are discharged into rivers, leading to biomagnification along aquatic food chains (Ali et al., 2019; Ahmed et al., 2019). Their effects on coastal environments and organisms can be substantial, in spite of restoration efforts (Mok et al., 2023). The

combined presence of these pollutants could result in synergistic detrimental effects. Studies on sentinel species offers interpretation of pollution levels and provide a comprehensive assessment of ecosystem impacts. Shorebirds exhibit crucial traits of sentinel species, such as clear responses to environmental variability, crucial roles in coastal food webs, and indicators of anthropogenic impacts on ecosystems (Hazen et al., 2019).

Long-distance migrant shorebirds, the most rapidly declining group of birds globally (Aarif et al., 2014; Aarif et al., 2020; Aarif et al., 2021a), rely on habitats and resources throughout their migratory routes. Anthropogenic mediated changes such as climate change and the loss or modification of their wintering and stopover grounds, are regarded as major causes of their population decline. Being apex predators in coastal ecosystems, shorebirds are highly vulnerable to environmental pollution owing to their unique migratory ecology and foraging behaviour (Aarif et al., 2023, 2024). Shorebirds of the Central Asian Flyway (CAF) have drawn attention due to recent long-term reports on their steady declining population trends and altered diversity in wintering grounds

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Tracing microplastics in environmental sources and migratory shorebirds along the Central Asian Flyway

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ABSTRACT

Microplastic pollution poses a significant threat to coastal ecosystems worldwide. Despite its widespread occurrence, knowledge on the prevalence and fate of microplastics across food webs is limited. To bridge this gap, we conducted an extensive study on microplastic contamination in mudflats, mangroves, and sand beaches being key habitats for wintering shorebirds on the west coast of India. Using a comprehensive multi-matrix approach covering water, sediment, biofilm, plankton, benthic macroinvertebrates, and migratory shorebird droppings, we analysed microplastic contamination across ten coastal sites from 2020 to 2022. Our findings show spatial and temporal variations in microplastics widespread in water and sediments, influenced by human activities. Notably, an increase in microplastics within prey and shorebird droppings coincide with a decline in prey abundance and shorebird populations. The prevalence of fibre-shaped microplastics indicates that common sources include discarded fishing gear and domestic sewage. The types of microplastics ingested by shorebirds varied depending on their feeding strategies, with biofilms serving as significant reservoirs of microplastics, facilitating their transfer to shorebirds. Epibenthic feeders, with a more limited foraging range, displayed the lowest levels of microplastics, while species foraging through multiple sediment layers exhibited higher concentrations. These findings underscore the urgent need for stricter conservation measures to tackle plastic pollution at its source. The study raises concerns about the potential harmful effects of microplastic contamination on the population of migratory shorebirds along the west coast of India. Continued research is crucial to understand the ecological impacts of microplastics on wintering shorebirds and to develop effective conservation strategies.

1. Introduction

Intertidal zones are among the most dynamic and ecologically significant coastal ecosystems that are critical for biodiversity and energy transfer through food webs (Leurs et al., 2023). These zones are categorized into sandy beaches, rocky beaches and mudflats, as well as

vegetated marshes and mangrove swamps (Murray et al., 2018). Characterized by alternating periods of exposure during low tide and submersion at high tide, intertidal zones are unique habitats where nutrient retention and enhanced primary productivity create ideal conditions for diverse biological communities (Leurs et al., 2023).

However, the proximity of intertidal zones to urban centres with

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SUMMARY AND CONCLUSIONS

This thesis presents a comprehensive evaluation of shorebird ecology along the west coast of India, integrating long term data on population trends, habitat use, foraging dynamics, adaptive behaviours, and contaminant exposure. Through extensive fieldwork and advanced analytical techniques, the study offers novel insights into the survival strategies and adaptability of shorebirds in response to environmental changes. The findings, published in ten reputed international journals, make a significant contribution to the global understanding of shorebird ecology and conservation.

Two near threatened species, the Eurasian Curlew (*Numenius arquata*) and Bar tailed Godwit (*Limosa lapponica*), exhibited marked population declines and shifts in habitat preferences. Peak abundances were recorded on sand beaches, diverging from their traditional mudflats and mangroves habitat. Dietary analyses identified seven primary prey types. Polychaetes and small crabs dominated the diets in mudflats and mangroves, while *Cosmonotus* crabs were most common on sand beaches. These findings highlight the urgent need for habitat restoration and targeted conservation measures to safeguard these migratory shorebirds.

Bar tailed Godwits showed higher foraging efficiency in mangroves, whereas Eurasian Curlews foraged more efficiently on sand beaches. These differences were influenced by a combination of sediment texture, prey behaviour, and species-specific morphological traits. Notably, a general decline in foraging success rates over time, except for a temporary rise during the pandemic lockdown, underscores the impacts of habitat degradation and human disturbances on shorebird foraging grounds.

A focused behavioural study of Bar tailed Godwits on sand beaches identified two distinct modes of continuous stitching: a straight line and a zigzag pattern. The zigzag mode was associated with higher prey capture rates and was closely linked to prey distribution. Despite disturbances and predation risk, Bar tailed Godwits maintained high foraging efficiency, demonstrating considerable behavioural plasticity in response to prey availability.

Long term assessments revealed significant environmental changes, particularly a decline in zooplankton productivity, signaling a broader depletion of coastal food web resources. This decline appears to have cascading effects on benthic macroinvertebrates and shorebird foraging success, prompting notable behavioural adaptations.

One such adaptation is the increased use of foot trembling, a foraging technique where birds create vibrations in the substrate to stimulate prey movement. This behaviour, more common under conditions of prey scarcity, was observed even in species not typically known to employ it, underscoring growing foraging pressures. Additionally, several prey transport mechanisms such as surface tension transport, inertial transport, and distal rhynchokinesis were documented under natural conditions, reflecting efficient and cost-effective foraging strategies.

A critical shift in habitat use was also recorded, with over-summering shorebirds increasingly utilizing inland agroecosystems as alternate habitats. This transition, driven by coastal habitat degradation, prey depletion, and escalating anthropogenic disturbances, marks a significant ecological shift in habitat selection.

Another major focus of this thesis was the assessment of environmental contaminants, particularly microplastics and heavy metals, across multiple ecosystem components. Microplastic pollution was widespread in water, sediment, biofilm, plankton, and prey species, with polyethylene, polypropylene, and polystyrene being the dominant polymers. Their detection in shorebird droppings indicates trophic transfer, raising concerns over long term ecological impacts. Simultaneously, heavy metals such as zinc, copper, cobalt, chromium, lead, and cadmium were present in alarming concentrations across trophic levels, highlighting the severity of anthropogenic pressures on coastal ecosystems and their potential effects on shorebird health.

In conclusion, this thesis underscores the urgent need for comprehensive habitat conservation, pollution control, and sustainable management of shorebird habitats.

The extensive datasets and novel insights generated form a strong foundation for future research, conservation planning, and policy interventions aimed at preserving the ecological integrity of coastal ecosystems and the survival of migratory shorebirds.



RECOMMENDATIONS

Based on the findings of this study, several conservation and management strategies are recommended to mitigate the decline of migratory shorebirds and protect their wintering grounds along the west coast of India. These recommendations encompass habitat restoration, pollution control, conservation policies, and further research to address knowledge gaps.

1. Habitat Conservation and Restoration

- *Protection of Intertidal Habitats:* The documented shift of Eurasian Curlew and Bar-tailed Godwit, both recognized as sentinel species indicating the health of intertidal ecosystems, from mudflats and mangroves to sandy beaches due to habitat degradation underscores the urgent need for conservation action. Priority should be given to restoring and preserving mudflats and mangroves, which support the highest foraging efficiency and dietary diversity not only for these species but also for a wide range of other wintering shorebirds dependent on these habitats along their flyway routes.
- *Enhancing Substrate Quality:* The degradation of foraging substrates due to sand deposition and pollution has significantly impacted shorebird populations. Strategies to reduce sediment hardening, such as controlled sand mining in the mudflats should be considered.
- *Mitigating mangrove incursion:* A scientific approach to monitoring mangroves should be adopted, with controlled removal in areas where unchecked expansion on to mudflats reduces foraging grounds of shorebirds.
- *Agroecosystem Management:* The increasing reliance of over-summering juvenile shorebirds on agroecosystems highlights the importance of maintaining these inland habitats. Sustainable agricultural practices that promote wetland retention and reduced pesticide use should be encouraged.

2. Pollution Control and Waste Management

- *Mitigating Microplastic Contamination:* Stricter regulations should be enforced to limit plastic waste discharge into coastal environments, particularly in riverine systems that act as major conduits of microplastics. Extended Producer Responsibility (EPR) should be strengthened to ensure that manufacturers actively participate in reducing plastic waste and promoting biodegradable alternatives. Public awareness campaigns should be launched to educate coastal communities about the long-term effects of microplastic pollution on shorebirds and broader ecosystems.
- *Heavy Metal Pollution Reduction:* Industrial discharges contributing to heavy metal contamination in shorebird foraging habitats must be regulated through stringent environmental monitoring and compliance frameworks. Efforts should focus on identifying and controlling pollution hotspots, particularly near major estuaries and industrial zones. Bioaccumulation studies on heavy metal transfer from sediments to shorebirds should be expanded to assess long-term impacts.

3. Conservation Policies and Legal Frameworks

- *International Collaboration for Migratory Species Protection:* Since shorebirds traverse multiple geopolitical boundaries, transnational cooperation among countries within the Central Asian Flyway (CAF) is essential. A unified conservation strategy should be developed to standardize habitat protection efforts, monitoring programs, and threat mitigation measures.
- *Incorporating scientific findings into conservation policies:* Research on shorebird ecology, habitat shifts, prey dynamics and habitat quality should be integrated into national and regional conservation policies. Decision making should be guided by long-term ecological data rather than short-term economic considerations

- *Adaptive mangement frameworks:* Policies should be flexible and updated regularly based on emerging scientific evidence.

4. Research Priorities

- *Shorebird Behavioural Ecology:* Further studies should investigate the influence of prey distribution and availability on foraging behaviour, particularly the adoption of uncommon foraging strategies in response to habitat changes.
- *Physiological Studies on migration:* The observed decline in capture success rates during March, contrary to conventional migration fueling patterns, warrants laboratory investigations on nutrient metabolism and physiological stress in shorebirds prior to migration.
- *Microplastic and Heavy Metal Interactions:* Research should focus on understanding the combined effects of microplastics and heavy metals on shorebird health, including bioaccumulation pathways and physiological consequences.
- *Impact of Climate Change on Prey Dynamics:* Given the potential shifts in benthic macroinvertebrate communities due to climate change, long-term studies should track changes in prey availability and their cascading effects on shorebird populations.
- *Multitrophic Studies on Coastal Ecosystems:* Integrated research on planktonic and benthic communities is necessary to predict and mitigate climate change-induced disruptions in coastal food webs.
- *Genetic and Evolutionary Studies on Shorebird Adaptation:* The observed use of agroecosystems as alternative habitats by over-summering juveniles could represent an evolutionary adaptation. Multi-generational genetic studies should be conducted to assess potential evolutionary responses to habitat changes.

5. Community Engagement and Public Awareness

- *Education and Awareness Campaigns:* Coastal communities, fisherfolk, and local decision-makers should be made aware of the importance of shorebirds and the threats they face. Raising awareness will help foster local support for the conservation of both shorebirds and the habitats they depend on.



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