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Mangrove forests as a natural trap for marine plastic litter: Insights from the Maldives

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ABSTRACT

Plastic pollution poses a significant threat to coastal ecosystems, including mangroves, which naturally trap debris due to their complex, three-dimensional structures. In the Maldives, inadequate plastic waste management exacerbates the accumulation of plastic in these critically endangered ecosystems, which are characterized by unique morphologies consisting of small patches with tide-influenced water bodies. Despite their ecological and socio-economic importance, mangroves in the archipelago have remained undocumented in terms of plastic pollution. This micro article presents the first evidence of plastic debris in Maldivian mangroves with accumulation observed on four islands dominated by species like *Ceriops tagal*, *Bruguiera cylindrica*, *Rhizophora mucronata*, and *Pemphis acidula*. The high tree density and the three-dimensional structure of these mangroves act as natural traps for marine litter, particularly single-use PET water bottles. These findings underscore the urgent need for conservation efforts and waste management policies to prevent further degradation and ensure their long-term sustainability.

1. Introduction

Plastic is an abundant solid contaminant in marine environments (Suyadi and Manullang, 2020), with an estimated 5–13 million metric tons of plastic entering the oceans annually (Jambeck et al., 2015; Geyer et al., 2017). Coastal habitats, along with the sea surface and submarine canyons, have long been recognized as hotspots for the accumulation of mismanaged anthropogenic marine debris (AMD), with plastics being the predominant (Cundell, 1973; Luo et al., 2021; Fallati et al., 2019). Among coastal ecosystems, mangroves have recently gained attention due to the growing threat of plastic accumulation in these habitats (De et al., 2023). Despite being one of the most biologically, ecologically, and economically important ecosystems globally, mangroves have been relatively understudied in terms of their role in trapping and accumulating macroplastics (Ivar do Sul et al., 2014; Martin et al., 2019; Serra-Gonçalves et al., 2019; Kesavan et al., 2021). Much of the existing research on marine plastic debris has focused on beaches (Derraik, 2002; Ryan et al., 2009; Costa et al., 2010; Martins and sobral, 2011; Chitaka and von Blottnitz, 2019; Thushari and Senevirathna, 2020; Sajorne et al., 2021), while studies on mangrove ecosystems have largely centered on microplastics in sediments (Mohamed Nor and Obbard, 2014; Zhou et al., 2020; Cordova et al., 2021; Deng et al., 2021; Maghsodian et al., 2022). Only 5 % of studies on marine debris have focused on coastal habitats other than beaches, including mangroves (Browne et al., 2015). This disparity may be attributed to the limited recreational and aesthetic appeal of mangroves compared to beaches, which has resulted in less governmental and societal interest in addressing plastic pollution in these ecosystems (De et al., 2023).

Mangrove forests play a significant role in trapping plastic debris due to their structural complexity and three-dimensional environment, which act as a natural filter (Martin et al., 2019; Kesavan et al., 2021; Luo et al., 2021). These characteristics contribute to higher densities of plastic debris in mangroves compared to beaches, with some studies reporting densities up to four times greater (Smith, 2012). In some places, such as the Maldives, challenging waste management systems can exacerbate the problem of plastic accumulation in mangroves. For decades, the country has struggled with inadequate waste management (Royle et al., 2022), producing approximately 860 metric tons of waste daily (World Bank, 2022), of which about 66 % of plastic waste is mismanaged (Karasik, 2022). In 2020, an estimated 1.6 kt of plastic waste entered the marine environment, primary due to leakage from the national landfill island (Royle et al., 2022) and mismanagement on rural

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inhabited islands with limited waste management facilities, as well as from boats navigating the atolls (Fallati et al., 2019). As a Small Island Developing State (SIDS) declared vulnerable by the 2010 UNPD's Assessment of Development Results, the Maldives faces heightened risks from plastic pollution, which can adversely affect key industries such fisheries and tourism that depend on pristine environments (Fallati et al., 2019; Suyadi and Manullang, 2020).

Mangroves in the Maldives are particularly distinct due to the absence of rivers and river mouths, resulting in unique morphologies consisting of small patches of closed or semi-enclosed brackish water bodies influenced by tides (Cerri et al., 2024). Of the 1192 islands in the Maldives, 108 host mangrove ecosystems, accounting for 9 % of the archipelago's total islands, with the highest concentration in the northern atolls (70.4 %) (Cerri et al., 2024). These small mangrove patches provide vital ecosystem services, including food resources, coastal protection, water purification, biodiversity support, and tourism value (Curnick et al., 2019; Cerri et al., 2024).

To date, no studies have documented plastic accumulation in the mangrove of the Maldives, making this article the first report on this phenomenon. Plastic mismanagement is a recognized problem in the Maldives, raising concerns that plastic debris may accumulate in coastal mangrove ecosystems. However, no studies have specifically investigated this issue. Given the ecological and socio-economic importance of these ecosystems, investigating plastic debris accumulation in the Maldivian mangroves is crucial for understanding the extent of the issue and its potential consequences. This descriptive micro article aims to provide initial evidence of plastic accumulation in Maldivian mangroves by documenting its presence across different islands and exploring potential environmental factors contributing to debris retention. Additionally, considering the unique and diverse characteristics of Maldivian mangroves (Cerri et al., 2024), this study investigates whether common habitat features influence plastic accumulation. By providing the first observational evidence of this issue, this descriptive study underscores the need for further research and targeted management strategies to mitigate plastic pollution in these vulnerable ecosystems.

2. Materials and methods

During three Marine Research and Higher Education (MaRHE) Center Mangrove Expeditions in 2024, observations were conducted across 28 islands from 10 different atolls, including Baa, Faafu, Haa Alifu, Haa Dhaalu, Kaafu, Laamu, Noonu, Seeny, Shaviyani, and Thaa. These islands were selected to ensure georaphycally representative sample of Maldivian mangroves, covering the northern, central, and southern regions. Selection criteria also included the presence of different habitat types, specifically open and closed mangrove ecosystems (Cerri et al., 2024). Surveys were conducted to visually assess plastic accumulation within mangrove areas. Observations were documented through photographs; habitat type was recorded; and the mangrove species present in each surveyed area were identified using the guide by Primavera et al. (2004). Surveys covered the entire extent of each mangrove forest, except for areas inaccessible due to dense vegetation or extremely muddy soil.

Fig. 1. a Map showing the islands where plastic accumulation was documented across the archipelago; b the embayment mangrove of Funadhoo Island; c plastic accumulation within the mangrove patch of Maaddoo Island; d plastic nets trapped among the roots of *Rhizophora mucronata* on Goidhoo Island; e plastic debris accumulation in the mangrove forest of Funadhoo Island; f plastic debris accumulation in the mangrove area of Dhiguvarufinolhu Island.

3. Results and discussion

During the surveys, 28 islands with mangroves were explored, and plastic debris accumulation was documented in four of them (14 %): Funadhoo, Dhiguvarufinolhu, Maaddoo, and Goidhoo (Fig. 1a). Funadhoo Island, an inhabited island located on the eastern edge of Shaviyani Atoll (Fig. 1b). The embayment mangrove forest here consisted of three mangrove species: *Ceriops tagal*, *Pemphis acidula*, and *Rhizophora mucronata*. The debris was largely concentrated in the eastern part of the island, in a narrow strip of land between the ocean and the bay. The ocean-facing side is characterized by stands of *P. acidula*, while the bay-facing side supports a dense forest of *C. tagal*. Most plastic debris, with single-use PET water bottles appearing to be a common type (Fig. 1e), were found trapped within the interior zone of the *C. tagal* forest. This suggests that the accumulation of debris likely originated from floating plastic litter, transported onto the island from the side facing the open ocean by strong wave action, possibly during the monsoon season. The debris passed through the initial barrier formed by *P. acidula* trees and was ultimately trapped and accumulated within the dense structure of the *C. tagal* forest, which acted as a natural barrier.

On Dhiguvarhufinolhu Island, a small uninhabited island on the eastern edge of Faafu Atoll, plastic debris was observed near a small tidal water body with two mangrove species: *P. acidula* and *Bruguiera cylindrica* (Fig. 1f). Plastic debris, with plastic bottles appearing to be the most common type, was predominantly trapped among the roots and dead stems of *P. acidula*. The tidal events, combined with wave action characteristic of Dhiguvarhufinolhu, likely facilitated the transport of plastic debris onto the island. The dense vegetation and three-dimensional structure of the mangrove forest then contributed to the trapping and accumulation of the debris.

Maaddoo Island, an uninhabited island on the southeastern edge of Baa Atoll, within the UNESCO World Biosphere Reserve, features a small patch of *B. cylindrica* mangrove trees near the coast. Plastic litter was observed within this mangrove patch (Fig. 1c). High waves likely transport debris into the mangrove patch, where the combination of the topography of the area, characterized by a slight depression, and the high density of young trees and seedlings effectively traps the plastic. In Goidhoo Island, also located in Baa Atoll, plastic accumulation was observed in a particular area near the entrance of the embayment mangrove. This flat zone, lacking adult trees and dominated by seeds and seedlings, is located adjacent to a dense stand of *R. mucronata* and *B. cylindrica* trees. Discussions with locals revealed that there is a program of periodic cleaning, as the mangrove forest is not only part of the UNESCO World Biosphere Reserve, but it was also designated as protected area under the Protected Area Announcement (IUL)138-FS2-1–2011-35. Furthermore, we noted plastic nets trapped within the root structures of the mature *R. mucronata* trees (Fig. 1d).

Several factors may explain why plastic bottles appeared to be a common component of plastic debris accumulation in the mangrove ecosystems of the Maldives. The presence of marine plastic litter in these areas is often attributed to tourism activity (Spalding and Parrett, 2019). However, none of the mangrove sites reported in this study are recognized as tourist destinations, unlike other mangrove forests in the Maldives. This suggests that the observed debris likely originated from the sea. Notably, single-use plastic bottles are the most common category of marine plastic debris in the Maldives, with their proportion significantly exceeding the global average (Royle et al., 2022). This trend is linked to the widespread preference for bottled water in the Maldives, a result of limited access to treated water in some local islands. The 2004 tsunami severely damaged underground freshwater reservoirs, leaving many islands reliant on rainwater collection or shipments of bottled water (Acciarri et al., 2021; Royle et al., 2022). As reported by Acciarri et al. (2021), a local island with only 800 inhabitants claims approximately 2300 l of bottled water per week (equivalent to about 1500 PET bottles) resulting in nearly 80,000 bottles annually (Karasik, 2022). While plastic bottle usage on local island is important, it is minimal compared to the consumption in the Capital, where, according to the Maldives Population and Housing Census 2022, about 41 % of the country population resides. In Malé alone, approximately 280,000 plastic bottles are used and discarded daily, adding up to over 102 million bottles annually (World Bank, 2022).

In Goidhoo island, we observed plastic nets entangled within the aerial roots of *R. mucronata*. These nets are likely remnants of discarded fishing and aquaculture equipment, a type of debris commonly reported in mangrove forest globally (Martin et al., 2019; Garcés-Ordóñez et al., 2019). Mangrove areas are integral to small-scale fisheries (zu Ermgassen et al., 2020; Luo et al., 2021), which may contribute to the presence of this debris. The prop root systems of *R. mucronata* provide both plant stability in dynamic environments (Srikanth et al., 2016) and an effective barrier for trapping debris, such as plastic bottles and nets (Luo et al., 2021). This dual function underscores their importance not only in coastal protection (Sánchez-Núñez et al., 2019; Vanegas et al., 2019), but also in debris retention (Luo et al., 2021). In contrast, the other three cases of plastic accumulation observed in this study, were not facilitated by stilt roots or pneumatophores, which are well-known for trapping plastic marine litter, particularly plastic bags (Cordeiro and Costa, 2010; Garcés-Ordóñez et al., 2019; Martin et al., 2019; Luo et al., 2021). Instead, the accumulations were primarily associated with *P. acidula*, *B. cylindrica* and *C. tagal*. While *B. cylindrica* and *C. tagal* are characterized by knee-roots, our observations suggest that these root structures were not prominent enough to serve as the main trapping mechanism. Rather, as in the case of *P. acidula* which does not possess specialized aerial roots like knee-roots or stilt roots, the high density of trees and the three-dimensional structure of the forest likely created natural barriers that trapped the debris. For example, in Funadhoo Island, plastic debris accumulated in the landward zone of a *C. tagal* forest, a phenomenon similar to that reported by Riascos et al. (2019), where dense tree stands restricted debris movement. The observed pattern suggests that the unique structural complexity and high density of these mangroves play a crucial role in plastic retention, particularly in less densely vegetated zones.

The distribution of marine plastic debris is generally influenced by various factors, including ocean circulation patterns, surface currents, prevailing winds, coastal and seafloor geomorphology, tides, and human activities (Barnes et al., 2009; Ramirez-Llodra et al., 2013; Eriksen et al., 2014; Fallati et al., 2019; Suyadi and Manullang, 2020; Van Der Mheen et al., 2020). Although these factors were not specifically investigated in this study, a common feature was observed among the four islands where plastic accumulation was documented. In each case, debris was concentrated in areas exposed to intense wave action, characterized by flat zones with slight depressions combined with dense vegetation of *B. cylindrica*, *C. tagal*, *R. mucronata* and *P. acidula*. Further research is needed to comprehensively assess the role of these factors in plastic accumulation and to determine the long-term retention or movement of plastic within mangrove ecosystems.

Although studies on the impact of plastic debris on mangrove health remain limited, existing research highlights several detrimental effects. Plastic trapped in mangrove systems can damage aerial roots and seedlings during tidal wave events (Cole et al., 2011; Martin et al., 2019). It can obstruct propagule growth, suffocate roots, and hinder photosynthesis, ultimately reducing soil quality and tree health. Prolonged exposure can result in tree mortality and forest degradation (Smith, 2012; Suyadi and Manullang, 2020; van Bijsterveldt et al., 2021; Luo et al., 2021; De et al., 2023). This underscores the urgent need for conservation efforts, and, particularly, waste management policies to prevent further degradation of mangroves of the Maldives. This urgency is heightened by their recent classification as critically endangered (IUCN, 2024), driven not only by improper waste disposal but also infrastructure development, illegal aquaculture, and overexploitation of resources, has been accelerating the decline (Curnick et al., 2019; Jaufar, 2021; Dryden et al., 2020; Cerri et al., 2024).

4. Conclusion

Our findings highlight the role of mangrove forests in the Maldives as natural sinks for marine plastic litter and emphasize the need for targeted conservation efforts. Future research should quantify plastic pollution and investigate its impact on mangrove health in the Maldives to better understand the long-term consequences of this issue, as well as the factors influencing plastic accumulation in these ecosystems. However, an immediate need must be the regular removal of trapped plastic debris through periodic cleaning programs, even on remote islands, to prevent further degradation of these critical ecosystems. By documenting the extent of plastic accumulation in mangrove forests, this study underscores the urgency of addressing the growing environmental challenge. Our findings also highlight that mangroves located near wave-exposed coastlines, with flat areas with areas characterized by slight depressions combined with dense vegetation, particularly of species such as *B. cylindrica*, *C. tagal*, *R. mucronata* and *P. acidula*, are more likely to retain plastic debris. As a result, these areas require greater efforts in their management to maintain ecosystem vitality. The findings provide a foundation for guiding policymakers and conservationists in implementing effective strategies to enhance the management and protection of these unique ecosystems. Ensuring the long-term sustainability of mangroves is not only essential for maintaining their ecological and economic benefits but also for preserving the natural heritage of the Maldives for future generations.

CRediT authorship contribution statement

Federico Cerri: Writing – original draft, Investigation, Conceptualization. **Shazla Mohamed:** Visualization, Validation. **Paolo Galli:** Supervision, Funding acquisition.

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Declaration of competing interest

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Data availability

Data will be made available on request.

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