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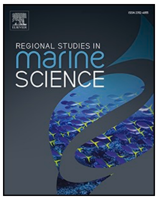

Mangrove species occurrence in relation to habitat types: Insights from the Maldives

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ABSTRACT

Mangroves are salt-tolerant woody plants forming coastal intertidal ecosystems throughout tropical and subtropical regions. Their distribution is commonly described along estuarine environmental gradients, with salinity and inundation identified as key drivers. However, in the Maldives, an oceanic archipelago lacking river systems, mangroves occur as small, fragmented stands of vegetation within closed or semi-enclosed water bodies, and their distribution patterns remain poorly understood despite the critical ecosystem services they provide. This study investigates species–habitat associations across 40 mangrove habitats, classified into embayment, pond-based, and marsh-based habitats, focusing on the occurrence of five dominant species: *Bruguiera cylindrica*, *B. gymnorrhiza*, *Lumnitzera racemosa*, *Ceriops tagal*, and *Rhizophora mucronata*. Water salinity was also measured to support interpretation of species distributions. Pearson's Chi-square tests detected significant associations between species occurrence and habitat type for the five species ($p < 0.05$), whereas differences in salinity among species were not statistically significant (Kruskal–Wallis test, $p = 0.208$). *B. cylindrica* (χ^2=20.000, $p < 0.001$) was strongly associated with marsh-based habitats, occurring in all surveyed systems of this type, whereas *B. gymnorrhiza* (χ^2=6.578, $p = 0.034$) was less frequent there; both species was observed across a wide range of salinities. *L. racemosa* (χ^2=8.189, $p = 0.020$) occurred most frequently in pond-based mangroves and was more often found in low to intermediate salinity conditions. In contrast, *R. mucronata* (χ^2=11.779, $p = 0.003$) and *C. tagal* (χ^2=23.022, $p < 0.001$) were predominantly associated with embayment habitats, characterized by high salinity. These findings improve understanding of mangrove spatial distribution and provide guidance for habitat-specific conservation and restoration in the Maldives, where mangroves are critically endangered.

1. Introduction

Mangroves are salt-tolerant woody plants that form coastal intertidal ecosystems throughout tropical and subtropical latitudes (Kathiresan and Bingham, 2001). They represent one of the most important ecosystems in terms of biology, ecology and also economy, providing habitat and food for several terrestrial and marine species and providing numerous ecosystem services, including coastal protection, carbon sequestration, and provision of natural products for drug discovery (Cerri et al., 2024; Cerri and Galli, 2025; Costanza et al., 1997; Dahdouh-Guebas et al., 2005; Polidoro et al., 2010).

Global mangrove flora comprises 65 true mangrove species (Kathiresan and Bingham, 2001), and species distributions in mangrove forests have long been described in terms of zonation along environmental gradients (Ball, 1998; Xu et al., 2020). Zonation arises from combining influence of flooding regime, salinity, sediment texture, propagule dispersal, interspecific competition, and climate (Ma et al., 2020; Xu et al., 2020), with salinity among the most consistently documented environmental drivers (Barik et al., 2017; Bunt, 1996; Duke et al., 1998; Ellison et al., 2000). These studies collectively show that

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mangrove species differ in their spatial distribution according to their ability to tolerate specific environmental conditions that characterize each habitat. For instance, whether species grow in saline, brackish or low-salinity environments largely depends on their different capacity to cope with salt stress (Ungar, 1991; Xu et al., 2020).

Most research on mangrove distribution has been conducted at the estuarine scale, where longitudinal gradients in salinity and inundation are well defined (Bunt et al., 1982; Costa et al., 2015; Smith and Duke, 1987; Xu et al., 2020). However, mangrove ecosystems do not always occur as extensive forest estuaries. In certain regions, such as the Maldives, an archipelago of 1192 small islands in the Indian Ocean lacking river systems, mangroves are typically found as small patches of vegetation within closed or semi-enclosed water bodies or muddy depressions (Cerri et al., 2024). Despite their ecological importance and the key ecosystem services they provide (Cerri et al., 2024; Nicolai et al., 2025), Maldivian mangroves have historically received limited scientific attention (Carruthers et al., 2024; Cerri et al., 2025; Louis et al., 2024) while most studies have focused on coral reefs and megafauna. Recently, Farhath et al. (2025) provided a comprehensive, archipelago-scale assessment of mangrove species and habitat types across the Maldives, outlining patterns of species distribution among different geomorphological settings. Building on this regional framework, the present study adopts a finer scale, analysing 42 independent mangrove habitats to investigate species-habitat association in greater detail. Based on ecological and morphological differences among species and established patterns of mangrove zonation, species occurrence was expected to vary among habitat types in the Maldives, reflecting adaptation to specific environmental conditions. Specifically, we examined whether the occurrence of five focal species (*Bruguiera cylindrica*, *B. gymnorrhiza*, *Lumnitzera racemosa*, *Ceriops tagal*, and *Rhizophora mucronata*) differs significantly among embayment, pond-based, and marsh-based habitats. In addition, given the recognized role of salinity in shaping mangrove distribution, water salinity was measured across sites to provide additional environmental context for the analysis of species-habitat associations.

This study provides a complementary perspective on the distribution of Maldivian mangroves, contributing to a better understanding of the environmental and spatial factors shaping species occurrence across the archipelago. Furthermore, understanding species distribution in relation to habitat typology is crucial for the planning ofmangrove restoration and conservation programs (Purwanto et al., 2022), as well as for marine spatial planning processes that guide coastal and island development. This is particularly important in the Maldives, where mangrove ecosystems have been recently classified as critically endangered (IUCN., 2024) due to improper waste disposal, infrastructure development, overexploitation, and climate change (Carruthers et al., 2024; Cerri et al., 2025; Sreelekshmi et al., 2025). At the same time, this study enriches the global pool of knowledge on this topic, contributing valuable data for broader comparative and biogeographical assessments of mangroves.

2. Materials and methods

2.1. Study design and habitat classification

Mangrove habitats were surveyed across 39 islands belonging to 12 different atolls of the Maldives during four Marine Research and Higher Education (MaRHE) Center mangrove expeditions in 2024 and 2025. Habitat classification followed the geomorphological scheme of Farhath et al. (2025) and was based on visual inspection of high-resolution satellite imagery (Google Earth Pro) combined with field-based confirmation during site visits. Classification relied on operational criteria to ensure consistency across sites, and habitat types were defined as follows. (i) Fringing mangroves: mangrove stands occurring along open coastlines or lagoon margins, directly exposed to the sea. (ii) Embayment mangroves: mangroves bordering a semi-enclosed coastal bay with direct connection to the sea. These systems were identified as recognizable coastal waterbodies partially surrounded by mangroves. (iii) Pond-based mangroves: mangrove stands surrounding a distinct inland waterbody (pond or shallow lake), characterized by a closed or nearly closed tree perimeter around a clearly identifiable central wetland area. These waterbodies, whether regularly shaped, irregular, or partially vegetated, were consistently distinguishable in satellite imagery. Water depth was not used as a classification criterion. (iv) Marsh-based mangroves: mangrove stands occupying low-lying depressions where surface water is shallow, seasonal or not distinctly visible in satellite imagery. These systems typically presented muddy or waterlogged substrates rather than a persistent inland waterbody.

Satellite imagery and field observation were used to identify the presence and geomorphological setting of each system. When multiple mangrove habitats occurred on the same island, they were considered independent habitat units only when clearly separated by terrestrial ridges, infrastructure or lack of observable hydrological continuity. To standardize surveys across habitats, roving visual assessments were conducted across the full extent of each mangrove habitat, except in areas that were inaccessible (e.g., dense vegetation, unstable soils), recording the presence of mangrove species. For pond-based and embayment mangroves, surveys followed the perimeter from the outer mangrove edge toward the inland margin to ensure complete coverage of each habitat unit. Each habitat was surveyed once during the field expeditions.

Fringing mangroves ($n = 2$) were limited in number and were therefore excluded from quantitative analyses. Furthermore, only five mangrove species were included in the analysis: *B. cylindrica*, *B. gymnorrhiza*, *L. racemosa*, *C. tagal*, and *R. mucronata*, as these species occurred in at least 10 habitats. Additional mangrove species were also recorded during the field surveys (*Rhizophora apiculata*, *Sonneratia caseolaris*, *Avicennia marina*, *Bruguiera hainesii*, *Excoecaria agallocha*, and *Pemphis acidula*), but these were not included in the statistical analyses because they occurred in fewer than 10 habitats or are considered controversial mangrove species in the Maldivian flora (Cerri et al., 2024). Species identification was performed visually using the identification guide of Primavera et al. (2004) and available literature (Sheue et al., 2005; Tomlinson et al., 1979; Selvam, 2007). Identification was further supported by the limited mangrove flora of the Maldives, where only 14 species are known to occur (Cerri et al., 2024).

Clear internal zonation along tidal flooding gradients was generally not observable across the surveyed habitats. Most systems consisted of shallow depressions or ponds with mangroves restricted to their margins, rather than extensive forests structured along elevation gradients. Consequently, inundation regime (e.g., water depth or flooding frequency) was not quantified as an environmental variable in this study. In contrast, salinity, which could be measured consistently across multiple sites, was evaluated to complement the habitat-based analysis.

For each mangrove habitat, GPS coordinates, habitat classification, water salinity value, and species present were recorded (Table S1). The distribution of study sites and examples of mangrove habitat types are shown in Fig. 1.

2.2. Salinity measurements

At each habitat, water salinity (PSU) was measured *in situ* at a minimum of three points using a handheld multiparameter probe (Hanna Multiprobe Meter, model HI98494, Hanna Instruments Inc., USA). Measurements were taken at representative points across each water body, and the mean value was used to characterize habitat salinity. In a few marsh- and pond-based habitats, measurements could not be obtained due to the absence of surface water or difficult access. Consequently, salinity data were available for 30 habitats.

Given the small size and hydrological variability of many of these systems, coupled with the pronounced seasonality of rainfall in tropical regions, salinity values should be interpreted as indicative, reflecting

Fig. 1. **a** Location of the Maldives within the Indian Ocean. **b** sSudy sites across the Maldivian archipelago, showing atolls (in red) and islands (in green); atoll names are indicated in white. **c, e** Example of pond-based mangrove habitat types (Thakandhoo and Dhapparu Islands, respectively). **d** Example of marsh-based mangrove habitat (Dhakandhoo Island). **f** Example of fringing mangrove habitat (Veymandhoo Island). **g** Example of embayment mangrove habitat (Funadhoo Island).

point-in-time conditions rather than long-term means. Measurements were not standardized across tidal stages or seasons and were therefore used to provide environmental context for interpreting species-habitat associations rather than to characterize long-term salinity regimes.

Salinity values are reported as mean ± standard deviation (SD) (Table S1).

2.3. Statistical analysis

Associations between mangrove species and habitat types were tested using Pearson's Chi-square (χ^2) test based on presence-absence data. Each of the five focal species was analysed separately across the three habitat categories (embayment, marsh-based, and pond-based). Since more than 20% of cells in contingency tables had expected frequencies below 5, a Monte Carlo exact test (based on 100,000 random tables) was used to estimate p-values, providing a robust alternative to asymptotic significance. For each test, χ^2 and degrees of freedom (df) were reported, while significance was interpreted from the Monte Carlo exact p-value. Standardized residuals exceeding $|2|$ were considered indicative of cells contributing significantly to the overall association. Cramer's V was calculated to estimate the effect size of each Chi-square test. Because each test examined the association between habitat type and the occurrence of a different species, analyses were considered independent, and no correction for multiple comparisons was applied.

Differences in species distribution according to salinity among habitats where each species occurred were tested using the non-parametric Kruskal–Wallis H test, as normality assumptions (Shapiro–Wilk, $p < 0.05$ for most species) were not met. All analyses were conducted in SPSS Statistics (version 29.0.2.0, IBM Corp), with significance set at $p < 0.05$.

3. Results

We reported 42 mangrove habitats across four geomorphological types: embayment ($n = 12$), fringing ($n = 2$), marsh-based ($n = 13$), and pond-based ($n = 15$) mangroves. To investigate patterns in species distribution among habitat types, we focused on the five dominant species: *B. cylindrica*, *B. gymnorrhiza*, *C. tagal*, *L. racemosa*, and *R. mucronata*. Particularly, *B. cylindrica* was reported in 22 habitats, followed by *R. mucronata* (16), *L. racemosa* (11), *C. tagal* (10), and *B. gymnorrhiza* (10). Given the limited number of fringing mangrove habitats, they were not considered for the analysis.

Species distribution was quantified as occurrence frequency, calculated as the percentage of habitats of each geomorphological type in which a given species was present (Fig. 2). *B. cylindrica* was recorded in all marsh-based habitats (13 of 13; 100%), while it occurred in only 2 of 12 embayment habitats (16.67%) and 5 of 15 pond-based habitats (33.33%). *B. gymnorrhiza* occurred in embayment (33.33%) and pond-based (40.00%) habitats, while it was absent from marsh-based habitats. *L. racemosa* was reported most frequently in pond-based habitats (53.33%), followed by marsh-based (15.38%), and embayment (8.33%) habitats. *R. mucronata* and *C. tagal* were predominantly found in embayment habitats (75% for both species); *R. mucronata* was also present in pond-based (40.00%) but was nearly absent from marsh-

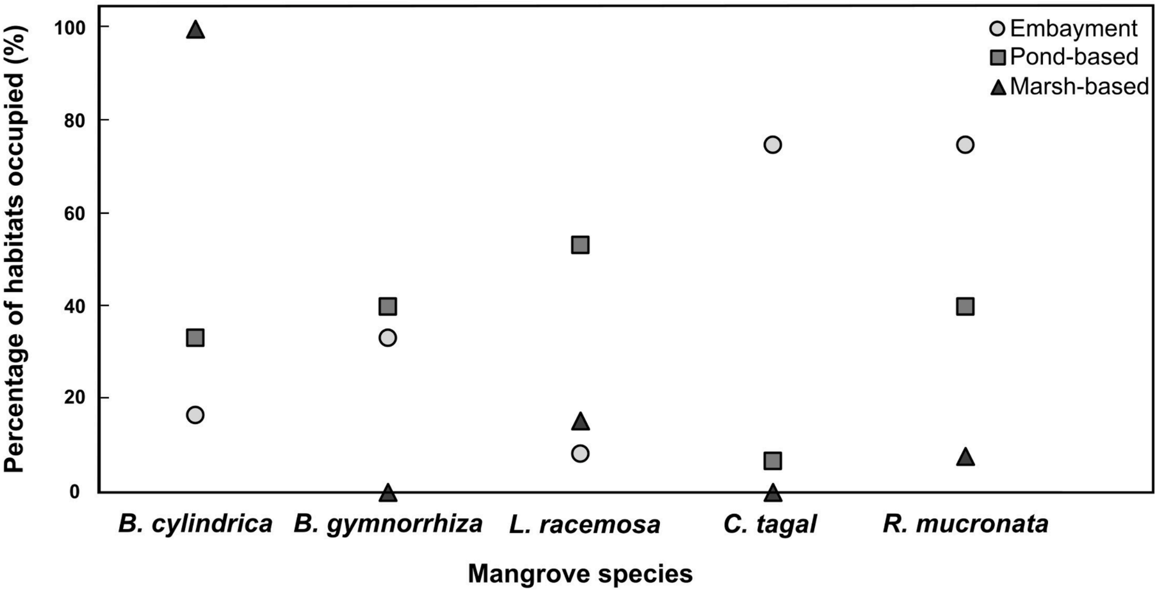

Fig. 2. Occurrence frequency of five dominant mangrove species across three habitat types (embayment n = 12, pond-based n = 15, marsh-based n = 13), expressed as the percentage of habitat units of each type in which a species was recorded. Percentages were calculated independently for each habitat type and therefore do not sum to 100% within species.

based habitats (6.67%), whereas *C. tagal* occurred infrequently in pond-based habitats (7.69%) and was absent from marsh-based mangroves.

Associations between mangrove species and habitat type were evaluated using Pearson's Chi-square test. Standardized residuals used to identify cells contributing to these associations are reported in Table S2 (Supplementary Material). *B. cylindrica* showed a strong and significant association with habitat type (Pearson's $\chi^2(2) = 20.000$, Monte Carlo exact test, $p < 0.001$; Cramer's V = 0.707) and standardized residuals indicated that the species occurred much more frequently than expected in marsh-based habitats (residual = +2.5). Its occurrence in embayment and pond-based habitats did not differ significantly from the expected frequencies. *B. gymnorrhiza* showed significant association with habitat type ($\chi^2(2) = 6.578$, Monte Carlo exact test, $p = 0.034$; Cramer's V = 0.406), as well as *L. racemosa* ($\chi^2(2) = 8.189$, Monte Carlo exact test, $p = 0.020$; Cramer's V = 0.452). Standardized residuals indicated overrepresentation of *L. racemosa* in pond-based habitats (+1.9). *C. tagal* showed a strong and highly significant association with habitat type ($\chi^2(2) = 23.022$, Monte Carlo exact test, $p < 0.001$; Cramer's V = 0.759) and standardized residuals indicated a significantly higher occurrence in embayment habitats (+3.5) and a strong but not

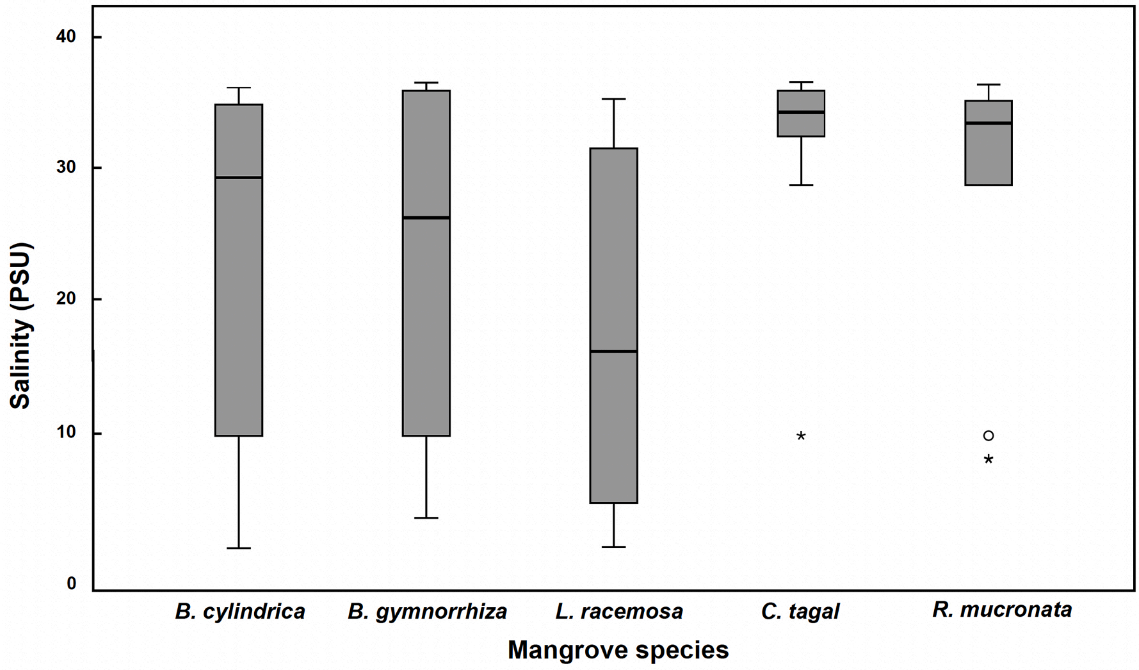

Fig. 3. Boxplots showing the distribution of water salinity (PSU) across habitats where each mangrove species was recorded. Central lines indicate median values, boxes represent interquartile ranges, and whiskers show the minimum and maximum values excluding outliers. Circles indicate outliers and asterisks indicate extreme outliers.

significant underrepresentation in marsh-based habitats (-1.8). *R. mucronata* showed a significant association with habitat type ($\chi^2(2) = 11.779$, Monte Carlo exact test, $p = 0.003$; Cramer's $V = 0.543$) and standardized residuals indicated much higher occurrence than expected in embayment habitats (+1.9) and lower occurrence in marsh-based habitats (-1.8).

In addition, water salinity (PSU) of the habitats was measured. Embayment systems were characterized by high salinity levels ranging from 27.62 PSU (Funadhoo bay) to 35.43 PSU (Farukolhu bay). Pond-based habitats showed much higher variability, with salinity values spanning from freshwater (0.23 PSU) to saline conditions (34.15 PSU). In marsh-based habitats, water was often absent or too shallow to measure salinity. When measurable, values ranged from 0.16 PSU (Kashidoo Island) to 35.01 PSU (Goidhoo Island). The distribution of salinity values across the three habitat types is illustrated in Figure S1 (Supplementary Material).

The distribution of the species along the salinity gradient is shown in Fig. 3. Differences in salinity among species were not statistically significant according to the Kruskal-Wallis test ($p = 0.208$). Nevertheless, salinity values across habitats spanned a wide range, from freshwater to marine conditions. *B. cylindrica*, *B. gymnorrhiza*, and *L. racemosa* were recorded across this broad salinity range. Among them, *L. racemosa* occurred in habitats with lower mean salinity values (16.56 ± 14.54 PSU), compared with *B. cylindrica* (22.20 ± 13.70 PSU) and *B. gymnorrhiza* (22.15 ± 13.15 PSU). In contrast, *C. tagal* and *R. mucronata* were observed mostly in habitats with relatively higher salinity values, with mean salinities of 30.58 ± 8.06 and 26.92 ± 11.25 PSU, respectively.

4. Discussion

Our results show differences in how mangrove species are distributed across habitat types in the Maldives, with most species occurring in all three habitat categories except for *C. tagal* and *B. gymnorrhiza* (Fig. 2). *B. cylindrica* occurred in every marsh-based mangrove habitat and was significantly overrepresented in this habitat type (standardized residual = +2.5). Marsh-based systems are typically shallow depressions characterized by waterlogged, muddy soils with variable or absent connection to the sea. The high occurrence of *B. cylindrica* in this habitat is consistent with its known landward spatial distribution (Sreelekshmi et al., 2018). Its aerial knee roots enhance gas exchange in oxygen-poor soils and provide anchorage in unstable muddy substrates (Nguyen et al., 2023; Srikanth et al., 2015; Tomlinson, 1986). In contrast, *B. gymnorrhiza* was not recorded in marsh-based habitats and occurred more frequently in pond-based and embayment systems, although no significant association with habitat type was detected. *L. racemosa* showed a distinct pattern, being significantly overrepresented in pond-based habitats and underrepresented in embayments. This agrees with previous studies reporting *L. racemosa* as abundant in landward or intermediate zones (Ma et al., 2020; Manohar, 2021; Sreelekshmi et al., 2018).

R. mucronata displayed the opposite trend: it was present in 75% of embayment habitats and positively associated with this category (standardized residual = +1.9), while being underrepresented in marsh systems. Embayment habitats in the Maldives experience strong tidal exchange (Louis et al., 2024), and *R. mucronata* is well adapted to such dynamic conditions characterized by inundation and sediment accumulation (Sreelekshmi et al., 2018). Its stilt roots confer stability, enhance sediment trapping, and allow aerial gas exchange (Srikanth et al., 2015), supporting its important role in coastal protection and shoreline stabilization (Batool et al., 2014.; Yoshikai et al., 2021). *C. tagal* also exhibited a high occurrence in embayment habitats (standardized residual = +3.5), in line with previous findings from the Sundarbans (Sreelekshmi et al., 2018).

The three habitat types investigated are distributed across islands throughout the northern, central, and southern Maldivian atolls. Therefore, the results of this study are not affected by broad climatic gradients such as temperature or rainfall. Differences in species distribution among habitats are unlikely to reflect large-scale geographic climate patterns. Instead, they are likely driven by local environmental factors, particularly salinity, given the well-established evidence that mangrove species occupy saline, brackish or low-salinity environments according to their different capacities to cope with salt (Ungar, 1991; Xu et al., 2020). Although salinity was not the primary focus of this study, it was measured to strengthen interpretation of species-habitat distributions. Given the small size of many of Maldivian mangrove systems and the pronounced seasonality of rainfall in the region, salinity values should be interpreted here as indicative.

Embayment mangroves exhibited consistently high salinity levels due to direct seawater exchange, while pond-based systems ranged from freshwater to hypersaline conditions, depending mainly on geomorphology and hydrological connectivity (Table S1). For example, salinity was extremely low in the enclosed inland pond of Gaadhoo, but intermediate or high in partially connected systems receiving seawater inflow. Marsh-based systems were similarly heterogeneous, ranging from shallow freshwater depressions to sites showing clear evidence of subsurface seawater inflow.

Mangrove species were recorded across a broad range of salinity conditions (Fig. 3). Although the Kruskal-Wallis test did not detect statistically significant differences in salinity among species, the observed salinity ranges provide contextual information for interpreting species–habitat distributions. *B. cylindrica* and *B. gymnorrhiza*, both salt excluders relying on root ultrafiltration (Palliyath and Puthur, 2018), occurred across a broad salinity range, mainly in medium to high salinity habitats. This is consistent with studies reporting *Bruguiera* species as abundant in the mid-salinity zone (Barik et al., 2017). *B. cylindrica*, in particular, can tolerate high salt concentrations (Palliyath and Puthur, 2018), although it can also dominate low-salinity sites (Perera et al., 2013). *L. racemosa*, a salt accumulating mangrove species (Palliyath and Puthur, 2018), also occurred across a wide range but was more common in low to intermediate salinity habitats, as previously reported (Barik et al., 2017; Dangremond et al., 2015; Perera et al., 2013), consistent with its underrepresentation in the embayment mangroves surveyed in this study.

R. mucronata and *C. tagal* displayed similarly high mean salinity values in their habitats (30.58 ± 8.06 and 26.92 ± 11.25 PSU, respectively), consistent with literature data (Barik et al., 2017) and attributable to ultrafiltration and additional physiological mechanisms (Khan and Aziz, 2001; Palliyath and Puthur, 2018). *R. mucronata*, in particular, is well known for its high salt tolerance (Aziz and Khan, 2001), which includes increased vessel density to facilitate water transport under hypersalinity (Schmitz et al., 2006) and the ability to accumulate and shed salt through mature leaves (Hoppe-Speer et al., 2011). This explains the strong associations of this species with embayment mangroves observed in this study. However, its occurrence also in medium-salinity pond-based habitats indicates that *R. mucronata* can grow across a wide salinity range (Purwanto et al., 2022). Indeed, although its seedlings have been documented to flourish at 26 PSU and thrive at 30 PSU, they also exhibited optimum growth at 8–18 PSU (Aziz and Khan, 2001; Barik et al., 2017; Hoppe-Speer et al., 2011; Jayatissa et al., 2008; Kathiresan et al., 1996; Purwanto et al., 2022). *C. tagal* is a highly salt-tolerant species and considered an indicator of high-salinity zones (Barik et al., 2017), due to physiological adaptations such as ion sequestration in leaf vacuoles, translocation of salts out of the leaf, and leaf turnover to facilitate salt shedding, together with an osmoconformer strategy (Aziz and Khan, 2001). Despite its tolerance, some works report its salinity optimum at 12.6 PSU (Patel et al., 2010). However, in our study, unlike *R. mucronata*, *C. tagal* was almost confined to embayment mangroves, likely due to lower competitiveness in less stressful habitats, as poor dispersal and establishment limit its colonization and population growth (McGuinness, 1996).

Overall, the patterns observed in this study reveal clear differences in habitat distribution among the five surveyed mangrove species in the Maldives. *B. cylindrica* showed a preference for marsh-based habitats and tolerated a broad salinity range. *C. tagal* and *R. mucronata* were both strongly associated with high-salinity embayment habitats, consistent with their known physiological tolerance to saline environments reported in previous studies, but with important differences. *C. tagal* was almost entirely confined to embayment habitats, suggesting a relatively restricted distribution among the surveyed habitat types, whereas *R. mucronata*, though most abundant in embayment systems, was also present in pond-based and marsh-based habitats. *B. gymnorrhiza* and *L. racemosa* were mostly recorded in pond-based habitats and were distributed across a broad salinity range, with *L. racemosa* more frequently recorded in habitats with low to intermediate salinity values. Together, these patterns demonstrate how species-specific traits interact with habitat conditions to shape mangrove distributions.

Inundation regime is widely recognized as another important factor influencing mangrove distribution. However, the characteristics of the surveyed systems, typically consisting of shallow depressions or ponds surrounded by mangroves restricted to their margins, make internal zonation along tidal flooding gradients generally not observable. In addition, several marsh-based habitats contained very shallow or apparently seasonal water. Consequently, this variable was not quantified in this study. Species occurrence was also assessed using presence–absence data, which allows identification of distribution patterns among habitats but does not capture differences in abundance or dominance within each system. Environmental measurements such as salinity represent indicative conditions at the time of sampling rather than long-term hydrological regimes. Therefore, future research should focus on mangrove systems where clear inundation gradients occur and include hydrological monitoring of water levels relative to microtopography and tidal cycles across different seasons, together with quantitative vegetation surveys, in order to better understand the drivers of mangrove distribution in the Maldives.

The distribution of mangrove species across habitats and salinity in the Maldives contributes to global knowledge on mangrove distribution and provides important insights for restoration and conservation efforts within the archipelago. Mangroves in the Maldives have recently been classified as critically endangered (IUCN., 2024) due to improper waste disposal, infrastructure development, overexploitation (Cerri et al., 2025), and a widespread dieback that affected approximately 25% of mangrove-containing islands, particularly marsh-based *B. cylindrica* forests. These ecosystems appear especially vulnerable to rapid sea-level rise and hydrological alteration (Carruthers et al., 2024; Sreelekshmi et al., 2025). This situation underscores the urgent need for effective conservation and restoration strategies in this Small Island Developing State. However, restoration efforts often fail due to the lack of scientific guidance, particularly regarding species selection and site suitability. Analyses of mangrove distribution can significantly improve the survival of restored forests (Hu et al., 2020; Lifeng et al., 2024). Therefore, the findings of this study can support authorities in implementing evidence-based management, conservation, and restoration strategies to ensure the long-term sustainability of mangrove ecosystems in the Maldives.

5. Conclusions

This study examined species-habitat associations across mangrove systems in the Maldives and revealed distinct patterns in how five dominant species are distributed among embayment, pond-based, and marsh-based habitats. *B. cylindrica* was significantly associated with marsh-based mangrove, while *L. racemosa* occurred most frequently in pond-based habitats. In contrast, *R. mucronata* and *C. tagal* were most commonly recorded in embayment habitats. Salinity measurements provided additional environmental context for these patterns, although differences in salinity distribution among species were not statistically significant.

These findings contribute to understanding the spatial distribution of mangrove species in the Maldives and provide useful information for conservation and restoration planning. Aligning species selection with the habitat types in which they most frequently occur may help improve restoration outcomes. This is especially critical in the Maldives, where mangrove ecosystems have recently been classified as critically endangered and where many systems, particularly marsh-based *B. cylindrica* stands, have recently experienced widespread dieback.

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CRediT authorship contribution statement

Giulia Senna: Writing – review & editing, Investigation. **Rossella Nicolai:** Writing – review & editing, Investigation. **Paolo Galli:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Shazla Mohamed:** Writing – review & editing. **Federico Cerri:** Writing – original draft, Visualization, Investigation, Data curation, Conceptualization. **Eleonora Concari:** Writing – review & editing, Investigation. **Yohan Didier Louis:** Writing – review & editing, Supervision, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rsma.2026.105001.

Data availability

All data supporting the findings of this study are available within the manuscript and its Supplementary Material.

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