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Research Article

Stress-Induced Dwarfism in *Avicennia marina* Across Coastal Gradients of the Red Sea and Arabian Gulf, Saudi Arabia

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Abstract

Background and Objective: *Avicennia marina* is the dominant mangrove species along the Saudi Arabian coasts of the Red Sea and the Arabian Gulf, where extreme environmental conditions frequently result in dwarf growth forms. This study evaluated regional variation in mangrove growth form and the distribution of dwarf stands across contrasting coastal environments. **Materials and Methods:** Field surveys were conducted during the first half of 2026 at 121 sampling sites distributed across the Northern Red Sea (27), Central Red Sea (37), Southern Red Sea (20) and the Arabian Gulf (37). Tree height was measured to classify mangrove growth forms and regional differences were analyzed using one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) test. **Results:** Tree height differed significantly among regions ($p<0.001$). The Northern Red Sea exhibited the lowest mean tree height (2.49±0.77 m) and the greatest prevalence of dwarf mangroves, whereas significantly taller trees were recorded in the Central Red Sea (3.67±1.22 m), Southern Red Sea (3.63±1.44 m) and the Arabian Gulf (3.68±1.31 m). These results demonstrate pronounced spatial variation in the structural development of *A. marina* along the Saudi Arabian coastline. **Conclusion:** *Avicennia marina* exhibits marked regional differences in growth form, with dwarf mangroves predominating in the Northern Red Sea. The findings establish a regional baseline for evaluating structural variability in *A. marina* and advance current understanding of mangrove dwarfism in arid coastal ecosystems.

Key words: *Avicennia marina*, mangrove dwarfism, structural variability, tree height, Red Sea, Arabian Gulf

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The grey mangrove species *A. marina* is the dominant mangrove taxon along the Red Sea and Arabian Gulf coasts of Saudi Arabia, where it frequently develops dwarf or structurally stunted growth forms under chronic environmental stress. These dwarf stands are characterized by low canopy height, reduced stem diameter and limited aboveground biomass, forming persistent low stature ecosystems rather than degraded transitional states. The Red Sea and Arabian Gulf provide two contrasting arid coastal environments for examining stress-driven mangrove dwarfism. In the Red Sea, mangrove growth is mainly constrained by oligotrophic conditions, limited freshwater input and nutrient deficiency, particularly nitrogen limitation[1,2]. In contrast, the Arabian Gulf is characterized by extreme hypersalinity, high summer temperatures and intense evaporation, where osmotic and thermal stress strongly suppress mangrove growth and productivity[3,4].

Dwarfism in *A. marina* results from interacting environmental stressors that limit carbon assimilation, physiological performance and biomass allocation. Hypersalinity reduces water uptake efficiency and stomatal conductance while increasing the energetic costs of ion regulation and salt secretion[5,6]. Nutrient-poor sediments further constrain photosynthesis and canopy development, especially in oligotrophic Red Sea systems[1,7]. Restricted tidal exchange also promotes sediment anoxia and sulfide accumulation, impairing root respiration and belowground productivity[8,9]. To survive under these conditions, *A. marina* exhibits adaptive mechanisms including salt exclusion and secretion, osmotic adjustment, improved water use efficiency, reduced leaf size and enhanced root development that collectively support tolerance to salinity and sediment stress[10-12].

Despite their reduced stature, dwarf *A. marina* ecosystems contribute important ecological and biogeochemical functions in Saudi Arabian coastal environments. Dense root systems enhance shoreline stabilization, sediment trapping and erosion control, while anoxic sediments promote long-term organic carbon preservation and blue carbon storage[13,14]. These systems also support active microbial communities involved in nutrient cycling and sulfur transformations under extreme environmental conditions[15,16]. However, reduced structural complexity may limit habitat diversity compared with taller mangrove forests.

Although the environmental factors contributing to mangrove dwarfism have been documented in previous studies, most investigations have focused on individual locations or specific stressors, limiting broader understanding of structural variability across contrasting arid coastal environments. Consequently, regional patterns in the growth form of *A. marina* along the Saudi Arabian coasts of the Red Sea and the Arabian Gulf remain insufficiently characterized. This study evaluates the structural variability of *A. marina* across these coastal systems by comparing tree height and associated morphological characteristics among the Northern, Central and Southern Red Sea and the Arabian Gulf. The observed regional patterns are subsequently interpreted in the context of published evidence to provide a comprehensive assessment of mangrove dwarfism under contrasting environmental conditions.

MATERIALS AND METHODS

Study area: This study was conducted in *A. marina* forests distributed along the Saudi Arabian coasts of the Red Sea and the Arabian Gulf (Fig. 1). Field surveys were conducted during the first half of 2026 across 121 sampling sites, comprising 27 sites in the Northern Red Sea (Madinah and Tabuk), 37 sites in the Central Red Sea (Makkah), 20 sites in the Southern Red Sea (Jazan and Asir) and 37 sites along the Arabian Gulf coast. Sampling sites were selected to represent the major mangrove clusters and the natural variation in forest structure across the Saudi Arabian coastline. The study area is characterized by a hyper-arid climate with extremely low annual precipitation, high evapotranspiration rates and prolonged periods of air temperatures frequently exceeding 40°C. Seawater salinity generally ranges from 38 to 45 PSU in the Red Sea and 45 to 70 PSU in the Arabian Gulf, reflecting contrasting environmental conditions across the two coastal systems.

Dwarfism driver network: A conceptual network model was constructed to represent interacting environmental and physiological drivers of dwarfism in *A. marina*. The network was developed through qualitative synthesis of published studies up to 2026. Key stressor nodes included hypersalinity, nutrient limitation, sediment anoxia, sulfide accumulation and hydrological restriction. Response nodes included reduced canopy height, altered biomass allocation, root-to-shoot ratio shifts, pneumatophore development and salt regulation mechanisms. Edges between nodes were defined based on documented causal or correlative relationships reported in the literature. Interaction strength was semi-quantitatively weighted according to frequency of reporting and consistency across studies. The resulting network was used to identify dominant stress pathways and integrated stress-response linkages controlling dwarf phenotypes.

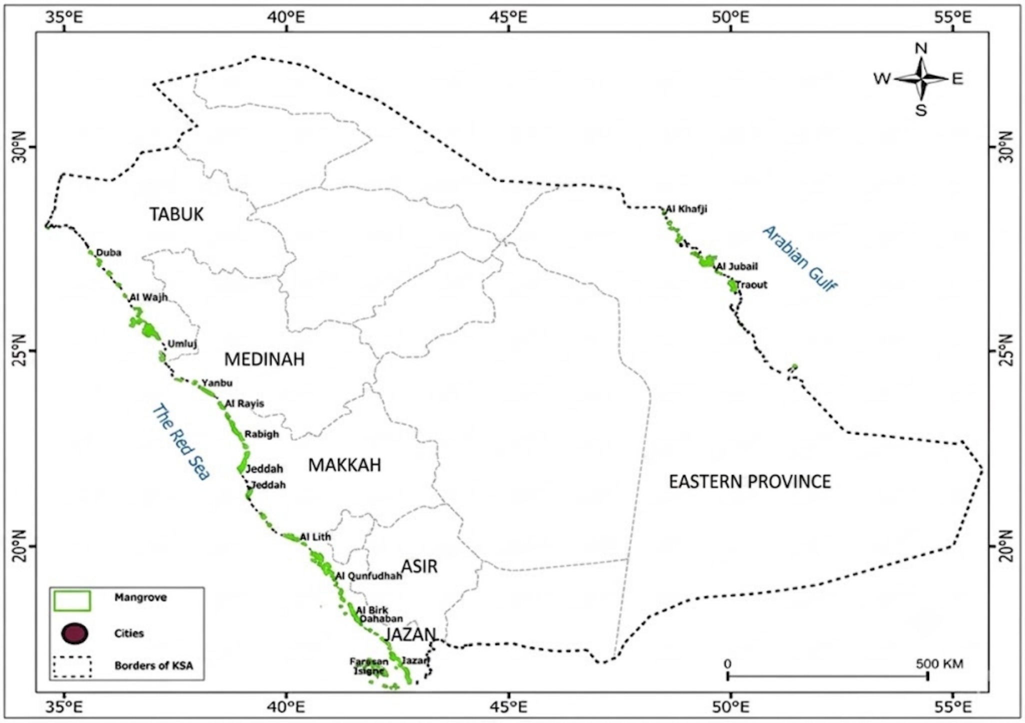

Fig. 1: Spatial distribution of mangrove forests along the Red Sea and Arabian Gulf coastlines of Saudi Arabia

Classification of mangrove growth forms: Mangrove growth forms were classified according to tree height, the most widely used structural indicator of mangrove dwarfism in arid environments. Following published descriptions of *A. marina* growing under hypersaline and nutrient-limited conditions, trees with a height of $\leq$2.5 m were classified as dwarf, those between 2.5 and 4.0 m as intermediate and those >4.0 m as well-developed (non-dwarf). This classification reflects the naturally reduced stature of *A. marina* in the Red Sea and Arabian Gulf, where environmental stress limits vertical growth compared with humid tropical mangrove forests. Tree height was selected because it directly integrates the cumulative effects of salinity, nutrient availability, hydrological conditions and physiological stress on long-term growth.

Statistical analysis: Tree height data were summarized using descriptive statistics and are presented as boxplots showing the median, interquartile range (IQR), whiskers (1.5×IQR) and individual observations for each study region. Differences in tree height among the Northern Red Sea, Central Red Sea, Southern Red Sea and Arabian Gulf were evaluated using one-way analysis of variance (ANOVA). When significant differences were detected, Tukey's honestly significant difference (HSD) *post hoc* test was applied to compare regional means. Different letters above the boxplots indicate statistically significant differences among regions at $p<0.05$.

RESULTS AND DISCUSSION

Dwarfism drivers: The principal environmental and physiological drivers underlying dwarfism and structural stunting in *A. marina* indicate that dwarf phenotypes emerge from interactions among multiple stress gradients rather than from a single limiting factor (Fig. 2). The network highlights oligotrophic nutrient limitation, particularly nitrogen and phosphorus deficiency, as a dominant driver of reduced canopy development and biomass accumulation, consistent with studies showing that nutrient-poor sediments constrain photosynthetic capacity, leaf nitrogen concentration and primary productivity in arid mangrove systems[1,2,7]. In the Red Sea and other carbonate-dominated coasts, nutrient scarcity is intensified by limited terrestrial inputs and restricted tidal exchange, resulting in chronically low nutrient availability that suppresses tree height and stand complexity. Hypersalinity and aridity form another strongly connected cluster, indicating that elevated porewater salinity and evaporative stress substantially reduce water uptake, increase osmotic stress and impose considerable metabolic costs associated with salt regulation and salt gland activity[3,5,17]. These conditions are particularly pronounced in hyper-arid coastal environments where salinity frequently exceeds physiological optima for *A. marina*, thereby restricting carbon

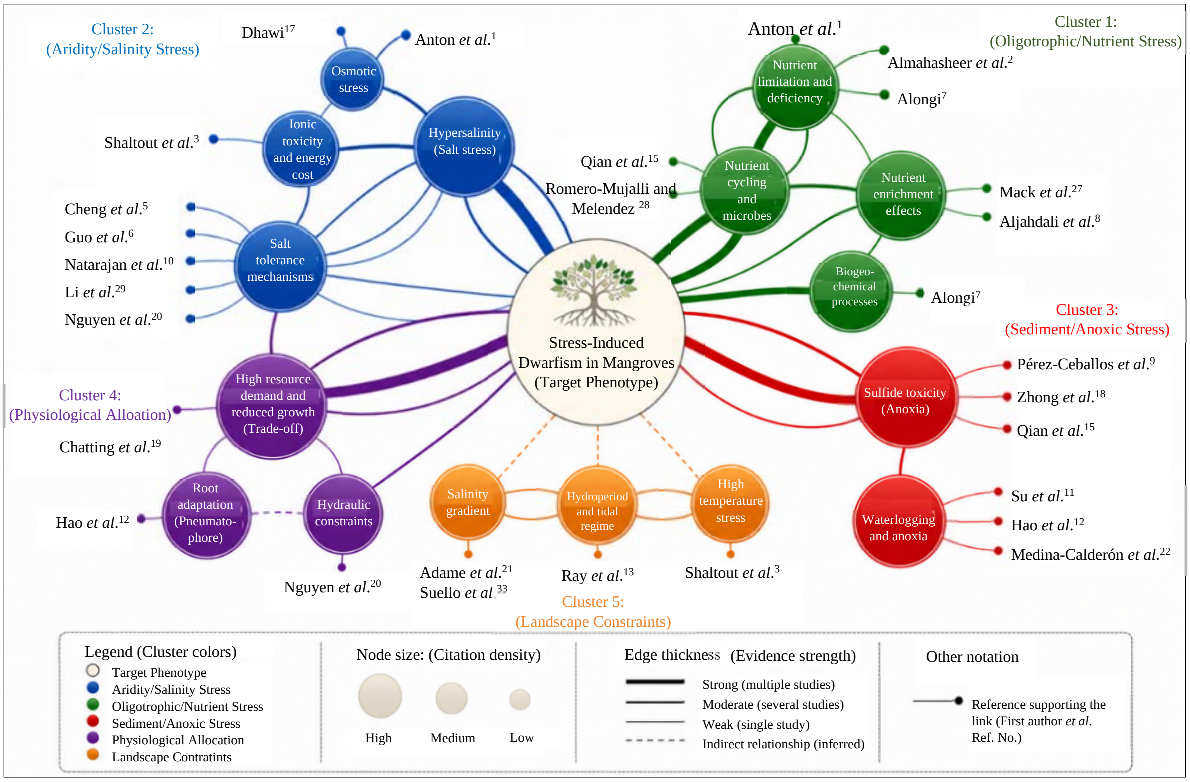

Fig. 2: Network-based conceptual framework of stress-induced dwarfism in mangrove ecosystems

Node sizes and edge weights reflect the relative citation density and strength of documented interactions linking specific environmental drivers (e.g., hypersalinity, nitrogen limitation, sulfide toxicity) to the target dwarf phenotype

allocation to vertical growth and promoting dwarf morphology. Sediment-related stressors also exert substantial influence on mangrove structural development, as sulfide toxicity, waterlogging and sediment anoxia impair root respiration, nutrient uptake and belowground oxygen diffusion, ultimately reducing productivity and regeneration capacity[9,14,15]. The network further indicates that physiological resource-allocation strategies are closely associated with dwarfism, with high root-to-shoot ratios, enhanced pneumatophore production and hydraulic constraints reflecting adaptive responses that prioritize belowground survival over canopy expansion under stressful conditions[12,18-20]. In addition, geomorphological and edaphic constraints associated with karstic and carbonate soils restrict freshwater retention and nutrient storage, further limiting forest structural development[21,22] .Taken together, these interacting stressors indicate that dwarfism in *A. marina* represents an integrated ecophysiological response to chronic environmental pressure, whereby nutrient limitation, salinity stress, sediment anoxia and physiological adaptation collectively constrain growth, reduce structural complexity and shape the persistence of dwarf mangrove ecosystems across extreme coastal environments.

Global comparative perspective: Globally, dwarf mangrove ecosystems represent convergent ecological responses to chronic environmental stress, with structurally reduced forests occurring across the Caribbean, Indo-Pacific, Australian, Mexican hypersaline and Arabian Gulf-Red Sea regions under varying combinations of hypersalinity, nutrient limitation, tidal restriction, aridity and hydrological isolation (Table 1). Caribbean dwarf mangroves, typically dominated by *Rhizophora mangle* in phosphorus-limited carbonate settings, exhibit canopy heights below 2-3 m and ecosystem carbon stocks of approximately 381-623 Mg C/ha despite suppressed productivity, largely because anoxic sediments slow decomposition[21]. Indo-Pacific systems, although globally recognized for exceptionally high mangrove carbon storage (>1000 Mg C/ha under optimal conditions), develop dwarf forms under salinity stress and restricted flushing, where reduced aboveground biomass is partially offset by greater belowground carbon allocation and root investment for osmotic regulation[23,24]. In Australian arid-zone mangroves, hypersalinity, evapotranspiration and nutrient-poor sediments constrain canopy development, producing shrub-like *A. marina* stands with relatively low biomass but persistent sediment carbon pools due to slow organic

Table 1: Comparative characteristics of global dwarf mangrove systems

Region	Salinity	Tidal restriction	Canopy height	Sediment condition	Dominant stressor	Carbon storage (Mg C/ha)
Caribbean dwarf mangroves	Moderate to high (35-60 PSU)	Moderate to high	1-3 m	Carbonate, phosphorus-poor soils	Nutrient limitation and salinity	~381-623
Indo-Pacific stressed systems	Variable; often high in arid zones	Variable	1-5 m	Muddy alluvial sediments	Hydrological stress and salinity	~400-1000+
Australian arid mangroves	High to hypersaline (>50 PSU)	Moderate	<2-4 m	Sandy to muddy sediments with low nutrients	Aridity and evapotranspiration	~200-600
Mexican hypersaline systems	Hypersaline (>60 PSU)	Severe	<1-2 m	Karstic, organic-poor sediments	Hypersalinity and tidal isolation	~381
Arabian Gulf/Red Sea *Avicennia marina* systems	Extreme hypersalinity (45-70 PSU)	Moderate to severe	<1-3 m	Fine sediments with high evaporation	Salinity, temperature, aridity	~150-350

Table 2: Comparative analysis of dwarf mangrove drivers and ecological characteristics between the Arabian Gulf and the Red Sea

Variable	Red Sea	Arabian Gulf	Dwarfism Driver
Canopy height	2-5 m	1-3 m	Reduced growth
Salinity	38-43 PSU	45-70 PSU	Osmotic stress
Summer temperature	35-40°C	45-50°C	Heat stress
Nutrient availability	Low (N-limited)	Very low	Reduced productivity
Tidal flushing	Moderate	Weak	Salt accumulation
Biomass productivity	Moderate	Very low	Lower carbon storage
Dominant stressor	Nutrient limitation	Hypersalinity+heat	Main cause of dwarfism
Leaf adaptation	Smaller leaves	Thick succulent leaves	Water conservation
Ecosystem impact	Moderate carbon loss	Strong carbon limitation	Reduced ecosystem function

matter turnover[25]. Similarly, Mexican hypersaline mangroves of the Yucatán Peninsula experience severe tidal isolation and porewater salinity often exceeding 60 PSU, resulting in canopy heights below 1-2 m and reduced biomass carbon, although soil carbon may still account for more than 80% of total ecosystem carbon stocks[21]. Comparable stress-driven dwarfism is also observed in Arabian Gulf and Red Sea *A. marina* systems, where extreme salinity, high temperature and aridity limit forest stature and reduce ecosystem carbon storage to approximately 150-350 Mg C/ha[19]. Collectively, these global comparisons demonstrate that mangrove dwarfism constitutes a functional adaptive strategy characterized by trade-offs between growth, carbon sequestration and stress tolerance, while maintaining important ecosystem services including shoreline stabilization, sediment retention, nutrient cycling and long-term blue carbon storage[24,26].

Dwarfism across Saudi coastal ecosystems: The comparative analysis reveals distinct regional differences in the drivers and expression of dwarfism in *A. marina* between the Red Sea and the Arabian Gulf (Table 2). Although both regions are arid and subject to persistent environmental stress, the Arabian Gulf is characterized by more extreme hypersalinity and thermal conditions, with salinity often reaching 45-70 PSU and summer temperatures exceeding 45°C. These combined stresses intensify osmotic constraints, reduce water uptake efficiency and severely limit canopy development, leading to highly stunted mangrove stands that frequently remain below 3 m in height. In contrast, Red Sea mangroves generally experience more moderate salinity levels (38-43 PSU), where dwarfism is more closely linked to nutrient limitation, particularly nitrogen deficiency under oligotrophic conditions. Empirical evidence from central Red Sea sites shows that mangrove height can decline to approximately 2.7 m, with a strong positive relationship between canopy height and leaf nitrogen content, emphasizing nutrient availability as a key growth regulator[1,2]. Structurally, both regions exhibit convergent dwarfing traits, including reduced leaf area, shortened internodes and low biomass accumulation, reflecting long-term adaptation to chronic stress. However, Arabian Gulf populations display more pronounced xeromorphic features such as thicker, more succulent leaves, extremely low productivity and greater suppression of biomass accumulation, consistent with stronger salinity and heat stress. Although A. marina is generally well adapted to hypersaline environments through salt secretion and osmotic adjustment, prolonged exposure to salinity beyond its physiological tolerance markedly restricts growth and regeneration[6,10]. Taken together, the evidence indicates that dwarfism in *A. marina* is governed by interacting environmental constraints whose relative influence varies regionally; nutrient limitation predominates in the Red Sea, whereas hypersalinity and extreme heat are the principal drivers in the Arabian Gulf, with important implications for mangrove restoration, blue carbon accounting and region-specific coastal management strategies.

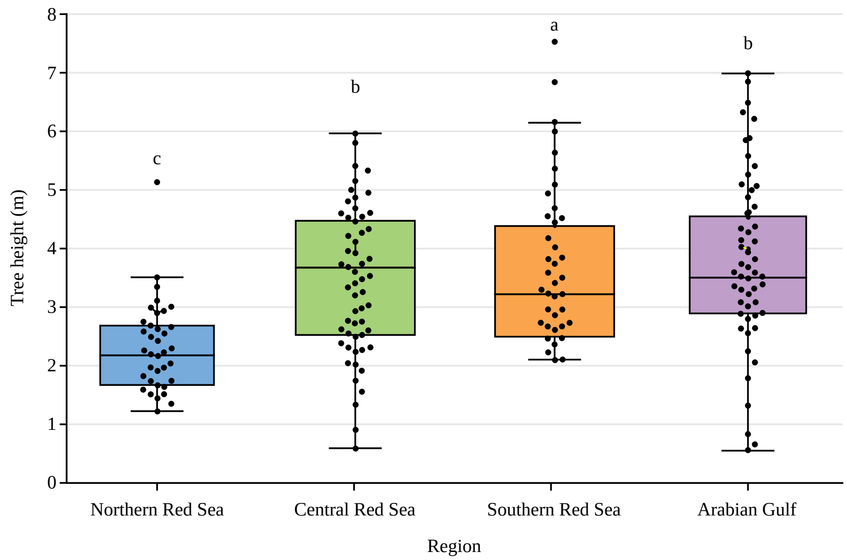

Fig. 3: Boxplots showing the variation in *A. marina* tree height among four coastal regions of Saudi Arabia
Boxes represent the interquartile range (IQR), horizontal lines indicate the median, whiskers represent 1.5×IQR and black dots denote individual observations. Different lowercase letters indicate significant differences among regions (Tukey's HSD test, p<0.05)

Variation in plant height: Tree height differed significantly among the four study regions (one-way ANOVA, F = 6.68, p<0.001), demonstrating pronounced spatial variation in the structural development of *A. marina* along the Saudi Arabian coastline (Fig. 3). The Northern Red Sea exhibited the lowest mean tree height (2.49±0.77 m; range 1.30-5.22 m), significantly lower than the Central Red Sea (3.67±1.22 m; 0.62-5.83 m), Southern Red Sea (3.63±1.44 m; 2.14-7.58 m) and Arabian Gulf (3.68±1.31 m; 0.60-7.00 m). Most individuals in the Northern Red Sea were between 1.5 and 3.0 m, indicating the predominance of dwarf mangrove stands, whereas the Southern Red Sea and Arabian Gulf supported the tallest individuals, reaching 7.58 m and 7.00 m, respectively. The relatively narrow interquartile range observed in the Northern Red Sea further indicates a consistently dwarf forest structure, while the broader distributions in the Central Red Sea, Southern Red Sea and Arabian Gulf reflect greater structural heterogeneity and variability in growth performance.

The reduced stature of *A. marina* in the Northern Red Sea is consistent with the combined effects of chronic environmental stress characteristic of hyper-arid coastal ecosystems. Although stand densities reached 8,000 trees/ha, trees remained relatively short, indicating that environmental conditions constrain individual growth rather than stand establishment. Across the Red Sea, seawater salinity generally ranged from 38 to 45 PSU, whereas considerably higher salinities were recorded in the Arabian Gulf (45-70 PSU). Nevertheless, tree height was lowest in the Northern Red Sea, suggesting that salinity alone does not explain the observed dwarfism. Instead, the combined effects of oligotrophic waters, extremely limited freshwater inputs, high evaporation rates, carbonate-dominated sediments and severe nutrient limitation appear to play a dominant role. Previous studies have shown that Red Sea mangroves occur under some of the most nutrient-impoverished conditions globally. Phosphorus is generally regarded as the primary limiting macronutrient in these carbonate-dominated oligotrophic systems, although nitrogen limitation may occur locally depending on sediment characteristics, nutrient availability and environmental conditions[2,4,27]. Carbonate-rich sediments strongly adsorb phosphate, reducing its bioavailability and limiting photosynthetic capacity, cambial activity and biomass accumulation. Consequently, the dwarf growth form observed in the Northern Red Sea likely represents an adaptive response to multiple interacting stressors rather than the effect of salinity alone.

In contrast, the significantly greater tree heights recorded in the Central Red Sea, Southern Red Sea and Arabian Gulf indicate comparatively more favorable local conditions for growth despite persistent environmental stress. The occurrence of trees exceeding 7 m in the Southern Red Sea and Arabian Gulf suggests that improved hydrological connectivity, sediment development and nutrient availability at specific sites can partially offset the adverse effects of high salinity. The wide range of tree heights observed in the

Fig. 4(a-d): Ecophysiological features of dwarf *A. marina* observed along the Red Sea coast, (a) Stunted dwarf mangrove stands under arid hypersaline conditions, (b) Reduced leaf size and partial leaf rolling associated with water conservation and stomatal regulation, (c) Isolated dwarf growth form with exposed pneumatophores in shallow coastal habitats and (d) Salt excretion and salt crystal accumulation on leaf surfaces under high salinity stress

Arabian Gulf (0.60-7.00 m), despite salinities of 45-70 PSU, further demonstrates that mangrove structure is strongly regulated by local hydro-edaphic conditions rather than by salinity alone. This interpretation is supported by previous studies showing that nutrient availability, sediment properties, tidal exchange and freshwater inputs frequently exert stronger controls on mangrove productivity than salinity within naturally established forests. Therefore, the pronounced regional differences in tree height observed in the present study highlight the remarkable morphological plasticity of *A. marina* and confirm that mangrove dwarfism along the Saudi Arabian coastline is driven by the interaction of salinity, nutrient limitation, sediment characteristics and hydrological processes rather than by a single environmental factor.

Adaptations under environmental stress: Integrated ecophysiological adaptations enable *A. marina* to survive under the hyper-arid and hypersaline conditions of the Saudi Red Sea coastline (Fig. 4). Exposure to elevated temperatures, intense evaporative demand, limited freshwater availability and saline sediments promotes pronounced phenotypic plasticity, resulting in the characteristic dwarf or stunted growth morphology observed across extensive mangrove stands (Fig. 4a). This reduced stature functions as an adaptive carbon-conservation strategy in which canopy expansion and biomass accumulation are constrained to reduce respiratory costs, minimize water loss and maintain metabolic balance under chronically resource-limited conditions. At the leaf level, reduced lamina size and partial leaf rolling (Fig. 4b) further decrease the transpiring surface area, thereby limiting excessive evapotranspiration and improving water-use efficiency through tighter stomatal regulation. In shallow intertidal habitats, the persistence of isolated dwarf trees depends on vertically elongated pneumatophores (Fig. 4c), which enhance oxygen diffusion into submerged, anoxic sediments and sustain belowground respiration during tidal inundation. Another key halophytic adaptation is the secretion of excess salts through specialized foliar glands (Fig. 4d). The accumulation of visible salt crystals on leaf surfaces reflects active exclusion of sodium and chloride ions, contributing to osmotic regulation, ion homeostasis and protection of cellular metabolic processes from salinity-induced toxicity. Collectively, these structural and physiological adjustments demonstrate that dwarf mangrove systems represent stable adaptive responses to chronic environmental stress rather than merely degraded forest conditions.

Comparable adaptive responses are evident in dwarf mangrove stands established in hypersaline coastal environments of the Arabian Gulf, Saudi Arabia (Fig. 5).

Fig. 5: Field example of dwarf grey mangroves (*A. marina*) in the Arabian Gulf, Saudi Arabia. Originally planted in the 1990s, these stands exhibit a pronounced stunted growth form associated with hypersaline conditions exceeding 50 ppt
Image also highlights the dense pneumatophore network, which facilitates gas exchange and supports root respiration under anaerobic sediment conditions

Although these stands were originally planted during afforestation initiatives in the 1990s, prolonged exposure to salinity levels exceeding 50 PSU has substantially constrained canopy development and biomass accumulation, resulting in persistent low-stature vegetation. The reduced tree height and patchy shrub-like architecture observed across the stands are characteristic of stress-induced dwarfism commonly reported in arid coastal systems with high evaporation rates, limited freshwater input and nutrient-poor sediments. Despite restricted aboveground growth, the dense network of pneumatophores emerging from the sediment surface highlights the importance of belowground adaptive investment under extreme environmental conditions. These specialized aerial roots facilitate oxygen transport to submerged root tissues under waterlogged and anaerobic sediments, thereby sustaining root metabolism and sediment respiration during tidal inundation. The extensive pneumatophore development further suggests a substantial allocation of resources toward stress tolerance and belowground survival rather than vertical canopy expansion. Together, these observations reinforce the view that dwarf mangrove systems in the Arabian Gulf constitute long-term ecophysiological adaptations to chronic hypersaline stress rather than evidence of ecosystem degradation alone.

Ecological and biogeochemical significance: Dwarf *A. marina* systems are ecologically and biogeochemically significant despite their low aboveground biomass and simplified canopy structure. These systems are instrumental in coastal protection through dense belowground root networks that enhance sediment trapping, reduce erosion and improve shoreline stability under hydrodynamic stress[28,29]. In hypersaline and nutrient-limited environments, dwarf mangroves also promote the accumulation and retention of organic matter within anoxic sediments, where low oxygen availability and reduced microbial activity slow decomposition and favor long-term carbon preservation[8,30]. This function is further reinforced by low litter turnover, limited tidal flushing and suppressed microbial mineralization, which collectively enhance sediment carbon storage and support blue carbon sequestration despite reduced primary productivity[31-33]. Moreover, dwarf mangrove rhizospheres sustain active microbial communities involved in nitrogen transformation, sulfate reduction and organic matter remineralization, thereby maintaining essential biogeochemical cycling under stressful environmental conditions[15,16]. However, reduced canopy complexity and simplified forest structure limit habitat heterogeneity, resulting in lower faunal diversity and abundance compared with structurally complex mangrove forests[34,35]. This reduction in structural complexity also constrains nursery and refuge functions for fish, crustaceans and other estuarine organisms[36,37]. Moreover, despite reduced biodiversity support, dwarf mangroves remain ecologically critical due to their strong contribution to sediment stabilization, biogeochemical cycling and long-term carbon storage in arid coastal ecosystems.

Current understanding of dwarf *A. marina* ecosystems remains constrained by limited long-term monitoring, insufficient quantification of belowground and microbial processes and a lack of integrative studies examining the combined effects of salinity, nutrient limitation, hydrological restriction and sediment redox dynamics. Environmental thresholds controlling transitions between dwarf and structurally developed mangrove forms also remain poorly resolved across regions, particularly in arid and hypersaline coastal systems that are underrepresented in global mangrove research. In addition, uncertainties persist regarding sediment carbon stability, microbiome functionality and ecosystem persistence under climate-driven environmental change. Future research should integrate long-term field observations, controlled multi-stressor experiments, remote sensing, molecular approaches and sediment biogeochemical analyses to improve mechanistic and predictive understanding of dwarf mangrove ecosystem functioning and stability.

CONCLUSION

This study demonstrates clear regional differences in the growth form of *A. marina* along the Saudi Arabian coastline, with the Northern Red Sea exhibiting the greatest prevalence of dwarf mangroves compared with the Central Red Sea, Southern Red Sea and the Arabian Gulf. The observed differences in tree height, together with documented structural characteristics and adaptive morphological traits, indicate that mangrove dwarfism is associated with persistent environmental stress in these arid coastal ecosystems. Comparison with published evidence suggests that the relative importance of environmental stressors differs between coastal regions, with nutrient limitation likely playing a greater role at several Red Sea sites, whereas hypersalinity and elevated temperatures are more influential in the Arabian Gulf. The adaptive traits observed in dwarf stands, including reduced canopy development, modified leaf morphology, enhanced pneumatophore development and salt secretion, demonstrate the remarkable phenotypic plasticity of *A. marina* under extreme environmental conditions. These findings provide a better understanding of the spatial variability of mangrove dwarfism in Saudi Arabia and offer a scientific basis for developing region-specific conservation, restoration and long-term monitoring strategies for arid mangrove ecosystems.

SIGNIFICANCE STATEMENT

This study provides the first regional assessment of dwarf *Avicennia marina* distribution along the Saudi Arabian coasts of the Red Sea and the Arabian Gulf. By identifying significant spatial variation in mangrove growth forms and highlighting the predominance of dwarf stands in the Northern Red Sea, the findings establish an important baseline for future ecological monitoring, climate change assessments and conservation planning. The results also improve understanding of mangrove structural adaptation to extreme environmental conditions in arid coastal ecosystems.

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