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Soil amendments improve growth and survival of grey mangroves in arid sabkha, Saudi Arabia

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Mangrove ecosystems are globally recognized as potent natural climate solutions due to their exceptional potential for carbon sequestration. Yet, they are rapidly declining under mounting anthropogenic pressures such as coastal urbanization, sea-level rise, and habitat conversion. This study investigates the viability of establishing *Avicennia marina* (grey mangrove) in an arid sandflat (known as sabkha) at two contrasting locations - Qurayyah and Rahimah - in the Eastern Province of Saudi Arabia. The main objective of this study was to compare the survival rate of *A. marina* mangrove seedlings between five soil amendments, namely, control, peat moss, Multi-microbial consortium (MMC) fertilizer and red soil. Results showed that peat moss, included for its high moisture retention and nutrient provisioning capacity, consistently achieved higher survival rates at both sites. In addition, peat moss consistently improved seedling survival at both sites. Multi-microbial consortium is recognized for its role in enhancing plant tolerance to salinity and facilitating nutrient uptake, particularly under nutrient-poor and saline conditions such as sabkha soils. In this study, Multi-microbial consortium-treated seedlings demonstrated notable improvements in nitrogen assimilation and chlorophyll content, highlighting the symbiont's contribution to enhancing physiological resilience under environmental stress. Notably Rahimah showed overall better survival outcomes than Qurayyah, likely due to its proximity to tidal waters. These findings indicate that the combination of appropriate soil amendments and closeness of sabkha to coastal waters is critical for improving mangrove survival in such environments. Overall, integrating targeted soil amendments with strategic site selection and optimized hydrological conditions could substantially enhance mangrove establishment, supporting climate-adaptive restoration in arid, hypersaline coastal systems.

KEYWORDS

arid coastal ecosystems, *Avicennia marina*, blue carbon, climate resilience, multi-microbial consortium (MMC), sabkha restoration, soil amendments

1 Introduction

Mangrove forests stabilize shorelines, support biodiversity, and store carbon (Reef et al., 2010; Reef et al., 2019; Macreadie et al., 2021). *Avicennia marina* (grey mangrove) dominates many Indo-Pacific and Arabian coasts and tolerates harsh conditions, high salinity, hypoxia, and nutrient-poor soils, through salt-secreting glands and pneumatophores (Thatoi et al., 2016). In the Arabian Gulf, however, restoration is challenged by hypersalinity (>40 ppt), very low rainfall (<100 mm yr⁻¹), high evapotranspiration, and rapid coastal degradation from industrial and urban development (Friess et al., 2019; Chang et al., 2020). As a result, natural regeneration is often weak, highlighting the need for improved restoration strategies (Chang et al., 2020).

A. marina establishment in hypersaline soils is mainly limited by osmotic stress during germination and early seedling growth. Although the species can mitigate salinity via salt compartmentalization, osmolyte production, and stomatal regulation (Duke, 2017; Friess et al., 2019; Nizam et al., 2022), restoration success is still constrained by extreme salinity and nutrient limitation. Trials from other arid coasts show that seawater dilution/controlled irrigation and propagule or substrate pre-treatments reduce osmotic shock and improve vigor, while targeted nutrient additions help sustain early growth under low rainfall (Naidoo, 1987; Naidoo, 2009; Kimera et al., 2024; Dhawi, 2025).

Substrate amendments are especially important in degraded sabkha soils. Organic materials (e.g., compost, peat moss, treated sewage sludge) can improve water retention, moderate temperature, stimulate microbial activity, and supply labile nutrients; in the Gulf, treated sewage sludge has increased survival and growth by improving moisture and nutrient availability across tidal cycles (Erftemeijer et al., 2021; Dhawi, 2025). Mineral fertilizers (balanced NPK) can also enhance growth, but excessive inputs in hypersaline soils can induce osmotic shock or toxicity, requiring careful dosing (Feller et al., 2003; Miah and Moula, 2019; Erftemeijer et al., 2021; Hsiao et al., 2024). Red soils/clays may further help by increasing water-holding capacity and nutrient retention, especially when blended with amendments such as perlite and fertilizers (Cao and Zhu, 1999; Lu et al., 2005; Ghasemi et al., 2010; Ghasemi et al., 2012). Biological amendments (Multi-microbial consortium) can improve nutrient uptake and stress tolerance, and actinobacteria-based approaches have shown promise in the Gulf, but field-scale tests, particularly for *mycorrhiza*, remain limited (El-Tarabily et al., 2021; Alkaabi et al., 2022; Sulistiono et al., 2024; Zeng et al., 2025).

Despite growing interest in substrate-based restoration, key knowledge gaps remain in the Arabian Gulf. Multi-site field trials that directly compare organic, mineral, and microbial amendments—alone and in combination—across contrasting hydrological settings are rare, and amendment effects are seldom evaluated in relation to site-specific tidal/hydrological context (Chang et al., 2020; Friis and Burt, 2020; Dhawi, 2025).

Gap: The relative performance of commonly used amendments under inland seawater-irrigated sabkha versus coastal tidally inundated sabkha is not well quantified.

Aim: We tested whether fertilizer, red soil, peat moss, and mycorrhizal inoculation improve *A. marina* seedling establishment in eastern Saudi Arabia by conducting replicated field trials at

Qurayyah (inland, high-salinity, seawater-irrigated) and Rhaimah (coastal, tidally inundated) from April–July 2025.

Hypotheses: (H1) organic amendments (peat moss; red soil mix) increase survival and improve growth/physiological status (height, chlorophyll, SPAD) relative to controls; (H2) mycorrhizal inoculation enhances foliar nitrogen and photosynthetic proxies under saline stress; and (H3) treatment benefits are stronger at the tidally inundated coastal site than at the inland seawater-irrigated site.

2 Materials and methods

2.1 Study area

The experimental study was conducted at two coastal sabkha sites located in the Eastern Province of Saudi Arabia: Qurayyah (26.12°N, 50.21°E) (Figure 1) and Rahimah (26.73°N, 49.99°E) (Figure 2). Both areas fall under an arid climate regime characterized by extreme summer temperatures (often exceeding 45 °C), minimal annual precipitation (<100 mm), and high soil salinity. Qurayyah lies approximately 1 km inland from the Arabian Gulf, while Rahimah is situated directly on the coast.

2.2 Pre-experimental soil assessment and site characterization

At both sites, four replicate soil samples were collected from the top 0–20 cm using a stainless-steel auger. Samples were air-dried, sieved (<2 mm), and analyzed for physicochemical properties. Texture was determined using the hydrometer method; pH and EC were measured in a 1:5 soil-to-water suspension. Nitrogen (N) was analyzed using Kjeldahl digestion; phosphorus (P) and potassium (K) using Olsen's and ammonium acetate methods, respectively. Exchangeable cations and micronutrients were measured via ICP-OES, along with heavy metals and sulphide. CEC was measured using ammonium acetate at pH 7. Qurayyah soil was classified as an Entisol with a sandy loam texture (89.6% sand, 6.8% silt, 3.6% clay), whereas Rahimah soil was identified as a sodic clay loam (32.4% sand, 28.6% silt, 39.0% clay). Qurayyah exhibited higher salinity (EC = 48,733 $\mu\text{S cm}^{-1}$) than Rahimah (EC = 45,100 $\mu\text{S cm}^{-1}$). In contrast, the cation exchange capacity (CEC) was lower at Qurayyah (159 meq 100 g⁻¹) compared to Rahimah (203 meq 100 g⁻¹), reflecting differences in clay content and nutrient retention capacity. These variations highlight the distinct edaphic challenges at each site, with direct implications for mangrove seedling establishment and soil amendment strategies (Table 1).

2.3 Plant material, nursery raising and acclimatization

Six-month-old *Avicennia marina* seedlings were incrementally acclimatized to saline conditions, starting with 10% seawater and increasing by 10% weekly until reaching 50%, with salinity levels checked weekly using a refractometer. Following salinity

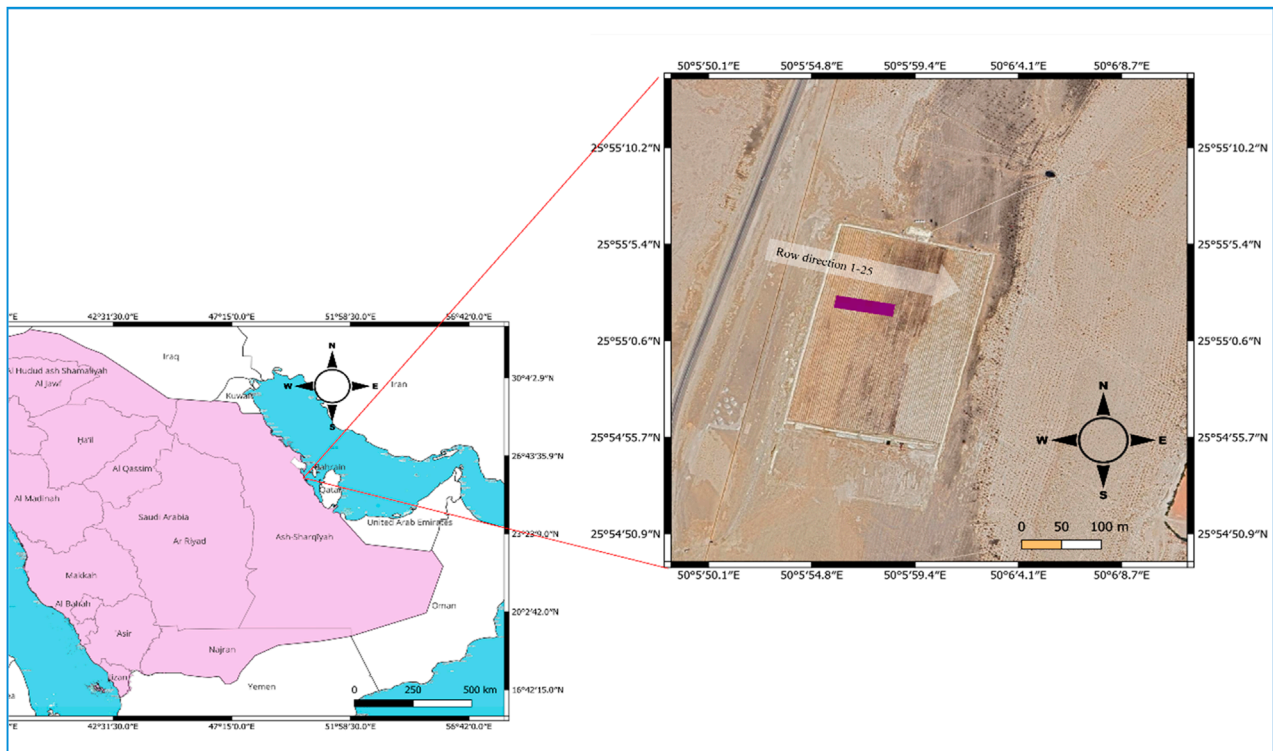


FIGURE 1

Study area and plot layout at the Qurayyah (QR) site, Eastern Province, Saudi Arabia. High-resolution basemap of the fenced experimental block with the purple bar marks the reference plot position. Axes are geographic coordinates (WGS84, EPSG:4326).

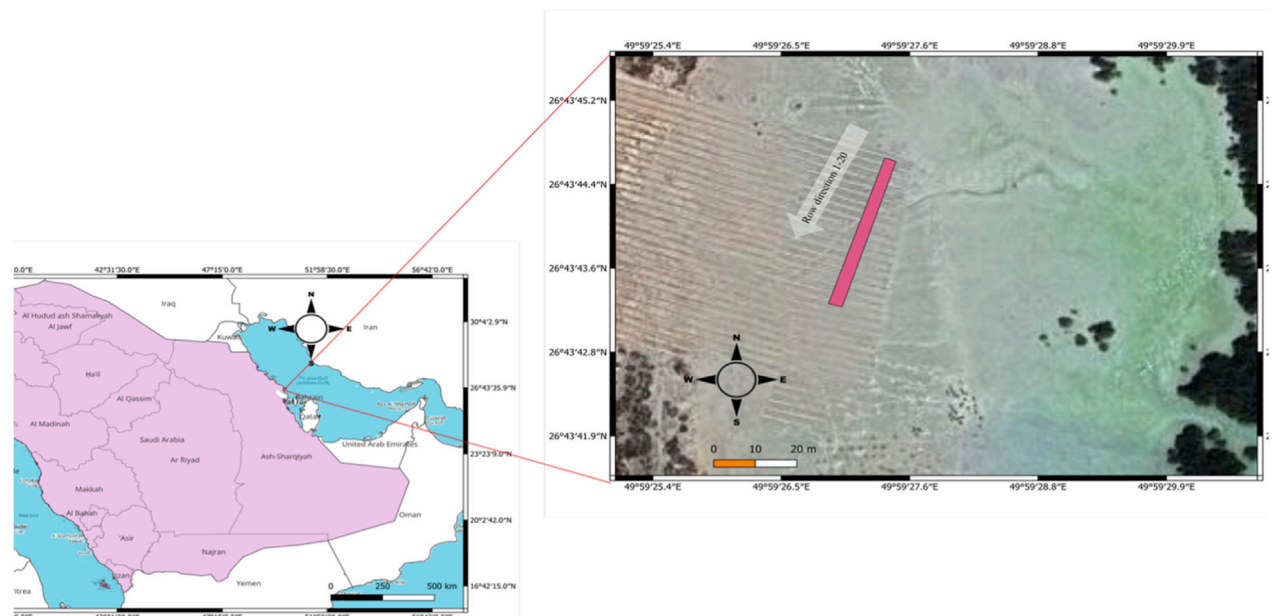


FIGURE 2

Study area and plot layout at the Rahimah (RH) site, Eastern Province, Saudi Arabia. High-resolution basemap of the experimental block with the pink bar marks the reference plot position. Axes are geographic coordinates (WGS84, EPSG:4326).

TABLE 1 Site-wise soil physicochemical metrics for Qurayyah and Rahimah; values are means $\pm$ SD (n = 4).

Parameter	Qurayyah soil	Rahimah soil
Soil texture	Sandy loam (89.6% sand, 6.8% silt, 3.6% clay)	Clay loam (32.4% sand, 28.6% silt, 39.0% clay)
Electrical conductivity (EC) ($\mu\text{S cm}^{-1}$)	48,733 $\pm$ 1,582	45,100 $\pm$ 0
pH	7 $\pm$ 0	8 $\pm$ 0
Total nitrogen (N) (mg kg ⁻¹)	119 $\pm$ 18.5	317 $\pm$ 45.1
Phosphorus (P) (mg kg ⁻¹)	268 $\pm$ 108.9	586 $\pm$ 211.1
Potassium (K) (mg kg ⁻¹)	717 $\pm$ 173.9	443 $\pm$ 106.6
Magnesium (Mg) (mg kg ⁻¹)	10,837 $\pm$ 7,736	14,367 $\pm$ 1,845
Calcium (Ca) (mg kg ⁻¹)	51,633 $\pm$ 35,891	20,933 $\pm$ 14,189
Sodium (Na) (mg kg ⁻¹)	6,540 $\pm$ 1,995	4,423 $\pm$ 1,000
Sulphide (S)	<1	<1
Cadmium (Cd)	<1	<1
Lead (Pb)	<5	<5
Chlorine (cl) (mg kg ⁻¹)	602 $\pm$ 66.4	18,250 $\pm$ 0
Copper (cu)	<0.1	<0.1
Zinc (Zn)	<0.1	<0.1
Manganese (Mn)	<0.1	<0.1
Boron (B)	<0.1	<0.1
Molybdenum (Mo)	<0.1	<0.1
Cation exchange capacity (CEC) (meq 100 g ⁻¹)	159 $\pm$ 48.2	204 $\pm$ 4.0

acclimatization, the seedlings were relocated to an open field in Qurayyah for light adaptation, receiving freshwater irrigation for the first week to minimize transplant shock. Subsequently, Qurayyah seedlings were irrigated daily with seawater, while Rahimah seedlings depended on natural tidal inundation. According to Santos et al. (2021), mangrove species adapt to saline gradients through physiological and morphological adjustments, with species-specific tolerances shaping their distribution and guiding effective ecological restoration strategies.

2.4 Experimental design

Field pilot trials were implemented under operational constraints at two contrasting sites in Eastern Saudi Arabia: Rahimah (RH; natural intertidal inundation) and Qurayyah (QR; inland sabkha dependent on pumped seawater). Treatments were applied in fixed spatial patterns to maintain practical site access and irrigation logistics. At QR, treatments were established as repeating row blocks (i.e., contiguous rows assigned to a treatment and repeated across the plot), whereas at RH the two treatments were arranged as alternating rows. Each treatment was represented by multiple replicated rows, and row ID was recorded for all observations. Because the field layout was not fully randomized, the row was treated as the primary experimental unit for survival and plant-response summaries (i.e., repeated measurements within a row were not treated as independent replicates).

2.4.1 Qurayyah experiment (inland site)

Five treatments were tested on 250 seedlings arranged in 25 rows (1 $\times$ 1 m spacing): control, peat moss, **multi-microbial consortium (MMC)**, urea, and red soil mix. Treatments were rotated every five rows.

- Control: no amendment
- Peat Moss: 5 kg per plant.
- **Multi-microbial consortium (MMC)**: 8 g inoculum (1.7×10^6 propagules) dissolved in 400 mL water per plant.
- Urea Fertilizer: 20 g per plant dissolved in 400 mL water.
- Red Soil Mix: 5 kg per plant of a 1:1:1:1 mixture of red soil, red clay, NPK fertilizer, and perlite.

A commercial multi-microbial consortium (Mikro-Myco[®], Microbial Applications Inc., United States), comprising arbuscular and ectomycorrhizal fungi, *Bacillus* spp. plant growth-promoting *rhizobacteria*, and *Trichoderma* spp., was used as a root inoculum. The formulation contained *Glomus* spp. (260 CFU g⁻¹), ectomycorrhizal fungi (218,000 CFU g⁻¹), *B. spp.* (4.0×10^8 CFU g⁻¹), and *T. spp.* (7.5×10^5 CFU g⁻¹). The inoculum was applied at a rate of 8 g per plant, dissolved in 400 mL of water, and applied as a root-zone drench at planting to ensure uniform distribution and direct root contact, a method commonly used to support early root establishment under water-limited (drought-prone) conditions. Soil conditions were monitored with five Hydra 100 sensors installed at 30 cm depth, measuring moisture,

salinity, and temperature (SIMOPS, Dammam, Saudi Arabia). The site was managed on a daily basis, including irrigation, while plant performance was assessed on a monthly schedule.

2.4.2 Rahimah experiment (coastal site)

Two treatments (Control and Peat Moss at 50 t/ha (5 kg/plant)) were tested on 200 seedlings across 20 rows. Control treatments were in odd-numbered rows and peat moss in even. Rows 1–11 were near the tide edge, frequently inundated, while rows 12–20 were further inland. This layout allowed comparison under differing tidal regimes. Plant performance was tracked monthly. To evaluate how hydrological gradients affect treatment performance, the experimental layout at Rahimah was designed to capture variation in tidal exposure. Rows 1–11, positioned closest to the shoreline, were frequently inundated by semi-diurnal tides. In contrast, Rows 12–20 were situated slightly inland at a modestly higher elevation, resulting in reduced and delayed tidal inundation due to subtle topographic variation. This spatial arrangement enabled analysis of seedling responses across a natural moisture and salinity gradient. Monthly tidal data, including frequency and height of high tides, were collected to link hydrological patterns with plant survival and physiological performance across treatments (Section 4.2; [Table 4](#)).

2.5 Hydrology, irrigation, and site-specific soil amendment design

At the Qurayyah (QR) site, seedlings received twice-daily irrigation with pumped Gulf seawater to mimic natural tidal inundation. Water salinity was regularly monitored using refractometer readings, while near-surface soil conditions (moisture, salinity, and temperature) were continuously tracked via Stevens HydraProbe 100 sensors installed at approximately 30 cm depth.

In contrast, at the Rahimah (RH) site, seedlings primarily relied on natural tidal inundation for irrigation. Marked differences in soil texture and hydrological regimes between the two sites required tailored experimental designs for soil amendments. Qurayyah is an artificially constructed supratidal platform irrigated solely by pumped seawater, characterized by coarse sandy loam soil (89.6% sand, 6.8% silt, 3.6% clay). Rahimah, a natural intertidal zone with varying elevations, experiences twice-daily natural tidal cycles as its primary water source and features finer clay loam soil (32.4% sand, 28.6% silt, 39.0% clay). At Rahimah, frequent tidal inundation combined with elevation-driven spatial variability positions hydrology as the dominant limiting factor for early mangrove establishment. To maintain operational realism and ensure unambiguous interpretation under highly dynamic tidal conditions, the pilot experiment was deliberately restricted to a simple two-treatment comparison: Control (no amendment) versus peat moss alone. Peat moss was selected as the most promising single amendment for this tidally influenced setting due to its established benefits in enhancing water retention, improving soil aeration, and increasing organic matter content, all while introducing minimal confounding variables. As a natural and eco-friendly material, peat moss can be readily substituted in future large-scale applications with locally available agricultural wastes, promoting greater sustainability and cost efficiency.

At Qurayyah, the supratidal location lacks natural tidal flushing, resulting in heightened exposure to stressors such as drought, salinity accumulation, and nutrient leaching issues intensified by the coarse-textured substrate and dependence on artificial irrigation. The controlled irrigation regime at this site permitted a more comprehensive multi-treatment experimental design, incorporating red soil, fertilizer, mycorrhizae, and peat moss (each applied individually). These amendments were chosen to directly counteract the site's key limitations: nutrient deficiencies, low water- and nutrient-holding capacity, and salt buildup. This site-specific strategy maximized ecological appropriateness, logistical feasibility, and the ability to isolate treatment effects against each location's prevailing environmental constraints. The resulting insights are therefore highly transferable to mangrove restoration initiatives across a wide range of coastal environments, including both natural intertidal zones and engineered supratidal platforms.

2.6 Data analysis

Meteorological variables (air temperature, relative humidity, wind speed) were obtained from local weather stations at Qurayyah (QR) and Rahimah (RH) and integrated with plant performance data collected from April to July 2025. At RH, tidal cycle data were also recorded to evaluate inundation effects. Plant health indicators including seedling height, SPAD values, chlorophyll concentration, and leaf nitrogen contents were measured monthly using standardized ecological protocols (meter stick, chlorophyll meter, spectrophotometer, and elemental analysis). Seedling survival rates were recorded monthly. Survival rate (%) was defined as:

$$\text{Survival rate (\%)} = \left(\frac{N_{\text{alive}}}{N_{\text{initial}}} \right) \times 100$$

Where:

- N_{alive} = number of seedlings alive at the assessment date (per treatment/plot)
- N_{initial} = number of seedlings planted initially (per treatment/plot)

Statistical testing of treatment effects on survival was performed on raw binomial count data (alive vs. dead) rather than on percentage values. To make this explicit, we revised [Table 2](#) (and [Table 3](#) where applicable) to report alive/total counts and sample sizes (n) for each treatment and sampling month; percent survival is shown only as a descriptive summary. All reported χ^2 p -values therefore derive directly from count-based contingency analyses using these alive/dead totals.

All datasets were preprocessed in R to address missing values and outliers, following established best practices ([Little and Rubin, 2019](#)). Soil datasets were analyzed using R (v. 4.3.1; [R Core Team, 2023](#)). Principal Component Analysis (PCA) was performed to reduce the dimensionality of the measured plant parameters (e.g., plant height, leaf nitrogen, SPAD values, and chlorophyll content) and to visualize the patterns of treatment response. PCA was

TABLE 2 Monthly survival of *Avicennia marina* at Qurayyah (April–July 2025) for Control and Peat Moss treatments, reported as survival (%) with corresponding χ^2 test results based on alive/dead counts.

Month	Comparison	χ^2 p-value
May	Control vs. red soil	0.046*
	Control vs. peat moss	0.014*
	Control vs. MMC	0.003**
	Control vs. fertilizer	0.779
June	Control vs. red soil	0.014*
	Control vs. peat moss	0.001**
	Control vs. MMC	<0.001***
	Control vs. fertilizer	0.008**
July	Control vs. red soil	0.224
	Control vs. peat moss	0.224
	Control vs. MMC	0.309
	Control vs. fertilizer	0.539

Values shown are p-values from chi-squared tests based on counts of alive versus dead seedlings. Significance levels: *p < 0.05, **p < 0.01, ***p < 0.001.

conducted using R-package “FactoMineR”. Normality was assessed using the Shapiro–Wilk test, and variance homogeneity with Levene’s test (Shapiro and Wilk, 1965; Levene, 1960). Treatment effects were evaluated by one-way ANOVA (p < 0.05), with pairwise differences tested using Tukey’s HSD (Tukey, 1949). Where assumptions were not met, the Kruskal Wallis test was applied (Conover, 1999).

3 Results

3.1 Qurayyah field experiment

At the inland Qurayyah site, five treatments (control, peat moss, multi-microbial consortium (MMC), urea fertilizer, and red soil mix) were evaluated on hardened *A. marina* seedlings from April to July 2025. Each treatment had 50 seedlings irrigated daily with seawater. By May, peat moss and MMC achieved the highest survival rates (>96%), outperforming Control (84%), though differences were marginally significant (p ≈ 0.051). This trend continued in June, with control seedlings declining further to 78%, in contrast to MMC (94%), peat moss (93%), and fertilizer (85%). By July, survival in the control group plummeted to 35%, whereas peat moss (48%) and MMC (47%) again showed the highest retention, followed by red Soil (45%) and fertilizer (42%). Peat Moss significantly increased foliar nitrogen in June (p = 0.03). Sensor data from the Qurayyah pilot study, recorded at 30 cm below ground from April to July, showed stable dry bulk density (1.4 kg/L). Soil moisture increased from 56.1% in May to 62.6% in June, while soil temperature remained steady (29.1 °C–29.5 °C). Conductivity rose (68.9–76.9 dS/m) as salinity decreased slightly (47.8–46.5 dS/m). Field capacity remained high (69.7–67.9), and water balance improved from 2.8 to 3.2 over the same period. No significant differences were observed between treatments.

TABLE 3 Survival rate (%) of plants under Control and Peat Moss treatments and corresponding Chi-squared test (χ^2 test) based on alive/dead counts. Significance levels results across months at Rhaimah.

Month	Treatment	Survival rate (%)	χ^2 p-value
May	Control	72	0.003
	Peat moss	94	
June	Control	57	<0.001
	Peat moss	91	
July	Control	20	<0.001
	Peat moss	81	

All treatments showed growth over time, although high data variability suggested the need for non-parametric tests (Chi-square tests). Peat moss and MMC were most effective in enhancing resilience, with pronounced effects observed in June, as detailed in Table 2 (Figures 3, 4; Table 2).

3.2 Rahimah field experiment

At the Rahimah coastal site, control and peat moss treatments were tested on 100 seedlings each under tidal irrigation. Survival dropped to 14% (Control) and 82% (Peat Moss) by June. Peat moss significantly improved SPAD (p = 0.01) and chlorophyll (p = 0.006) early in the season. Rows near the tidal edge (1–11) had higher survival than inland rows (12–20). Temperature, humidity, wind, and solar radiation strongly influenced survival (r = –0.99 for temperature). Peat moss consistently mitigated stress (Figures 5, 6; Table 3).

Monthly survival trends of *Avicennia marina* seedlings under control and peat moss treatments at the Rahimah (RH) site revealed a consistent and statistically significant advantage of the peat moss treatment over time. Survival was uniformly high (100%) across both treatments in April, precluding statistical comparison for that month. However, from May onwards, survival in the control group declined sharply, while seedlings treated with peat moss maintained significantly higher rates of survival.

In May, survival dropped to 72% in the control group, compared to 94% in the peat moss group (p = 0.003). This disparity widened in subsequent months: by June, survival declined to 57% in the control versus 91% in peat moss; and by July, control survival fell to just 20%, while peat moss-treated seedlings retained 81% survival (p < 0.001 for both months). These differences were corroborated by chi-squared test results, which confirmed statistically significant variation in survival distributions across treatments over time.

3.3 Treatment effects and climate influence

At Qurayyah, Chi-squared tests showed that peat moss, mycorrhiza, and red soil mix significantly enhanced survival in May and June, but differences faded by July due to extreme heat. Peat moss improved nitrogen content and photosynthetic traits

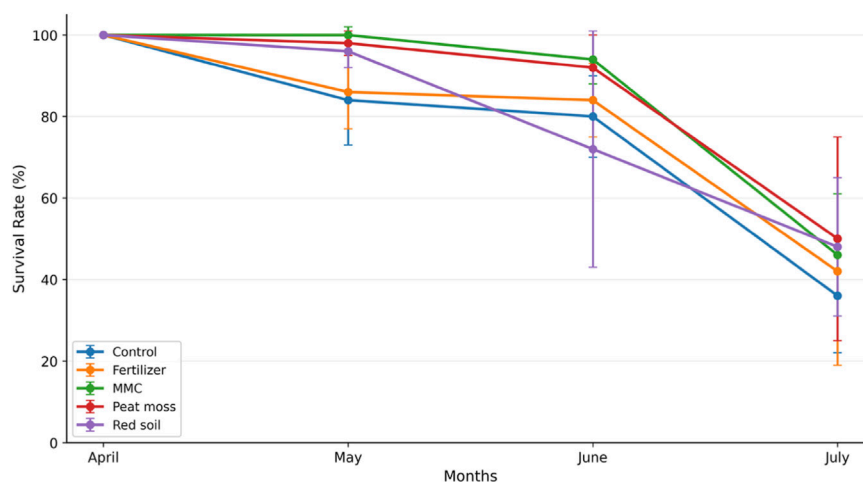


FIGURE 3

Average survival rates of *Avicennia marina* seedlings at the Qurayyah (QR) site from April to July 2025. Values represent mean survival percentages across treatments, highlighting the differential effectiveness of soil amendments in enhancing mangrove performance under arid, inland hypersaline conditions.

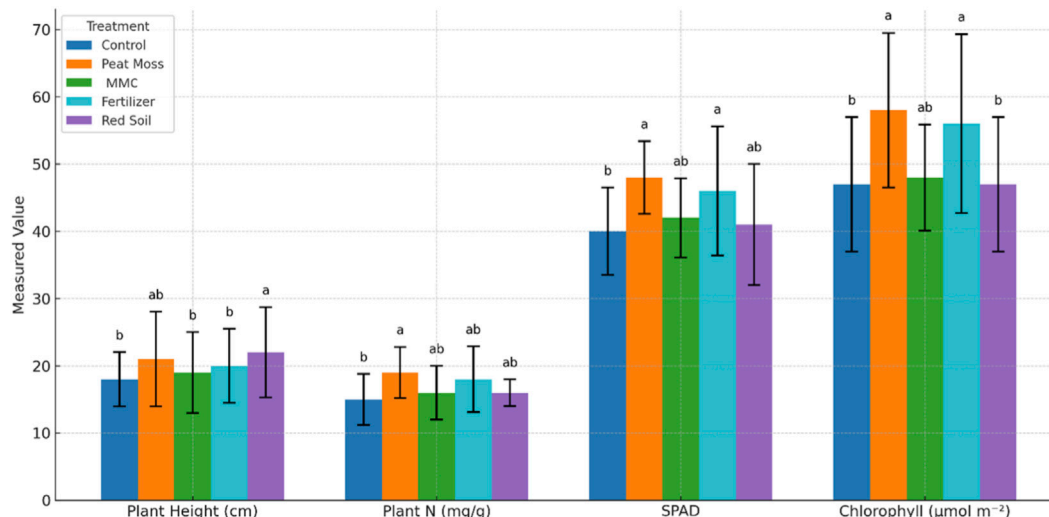


FIGURE 4

Mean physiological parameters of *Avicennia marina* seedlings under different soil amendment treatments at the Qurayyah (QR) site in July 2025. Values represent treatment mean $\pm$ standard deviation (SD) for plant height, nitrogen concentration, SPAD readings, and chlorophyll content ($\mu\text{mol m}^{-2}$), illustrating the comparative effects of soil amendments on seedling performance under inland hypersaline conditions. Different letters above bars indicate significant differences among treatments within each parameter, based on Tukey's HSD test ($p < 0.05$). A full dataset with detailed values from April through July 2025 is provided in the Appendix.

significantly ($p < 0.05$). Red soil mix promoted height although was not statistically significant (Table 2). At Rahimah, peat moss showed strong survival advantage across months (81% in July vs. 20% control). Survival positively correlated with soil moisture and negatively with rising temperature, salinity, and wind speed. The sharpest survival declines occurred during peak summer conditions in July at both sites. At RH, tidal inundation provided periodic rewetting, but micro-elevation and exposure differences remained evident in later-season outcomes. Monthly tidal context summaries are provided in Table 4.

3.4 Row-level and physiological analysis

Row-level data at Rahimah revealed sharp declines in control survival (58% by June) versus consistent performance under peat moss. Rows 1–11 near the tidal edge had better outcomes than inland rows. SPAD and chlorophyll peaked in May under peat moss, although summer stress reduced performance in both treatments. Halophytes like *Salicornia spp.* were observed in drier plots (Rows 18–20), indicating a shift in vegetation with declining tidal influence.

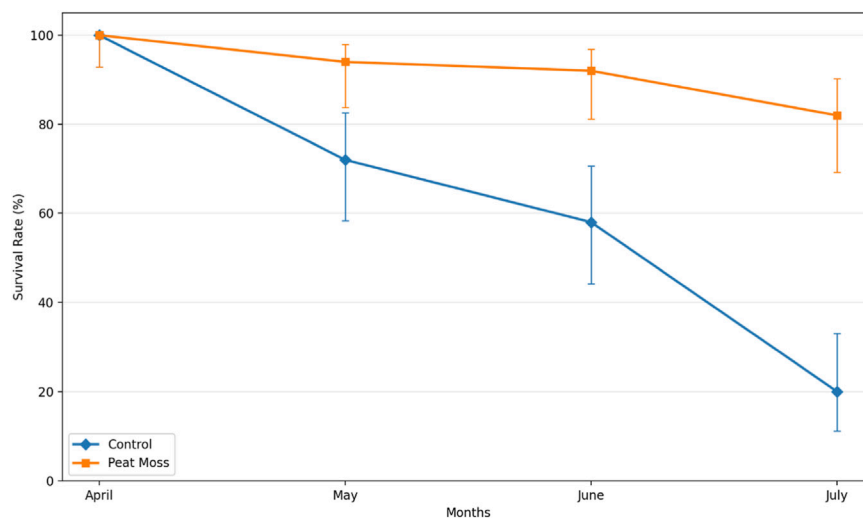


FIGURE 5

Average survival rates of *Avicennia marina* seedlings under different soil amendment treatments at the Rhaimah (RH) site from April to July 2025. The figure illustrates the comparative performance of treatments in enhancing mangrove survival under natural tidal and hypersaline coastal conditions.

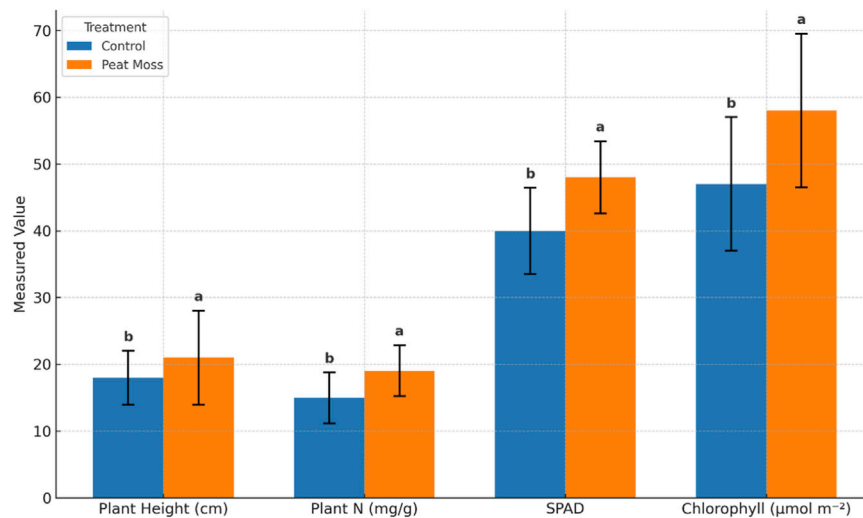


FIGURE 6

Average key physiological indicators of *Avicennia marina* seedlings under different soil amendment treatments at the Rahimah (RH) site from July 2025. Data represent treatment mean $\pm$ standard deviation (SD) for chlorophyll content, SPAD values, nitrogen concentration, and plant height, illustrating the comparative effects of each intervention on mangrove performance under tidal hypersaline conditions. Different letters above bars indicate significant differences among treatments within each parameter, based on Tukey's HSD test ($p < 0.05$).

3.5 Multivariate analysis of treatment responses at Qurayyah and Rahimah

3.5.1 Qurayyah

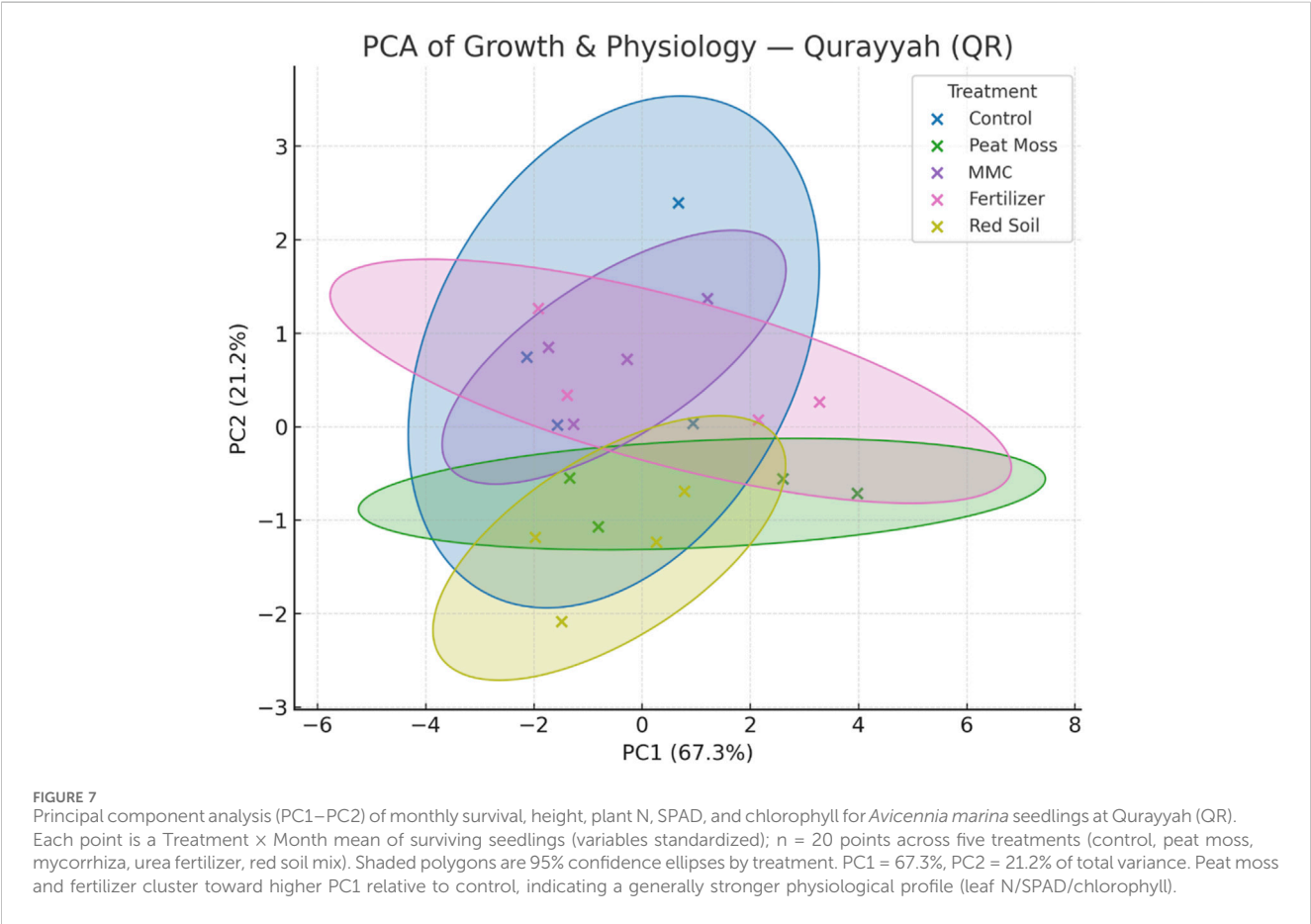
Principal component analysis (PCA) of survival, height, plant N, SPAD and chlorophyll separated treatments primarily along PC1 (67.3% variance), which loaded positively on plant N, SPAD and chlorophyll and negatively on survival; PC2 (21.2%) reflected plant height (higher height $\rightarrow$ lower PC2) (Figure 7). The peat moss and fertilizer groups formed right-shifted clusters with higher

PC1 scores, indicating a consistently better physiological status across months relative to control. Control occupied the low-PC1 region, consistent with lower chlorophyll/SPAD and declining performance by July. Red soil tended toward lower PC2 (taller plants), while MMC overlapped centrally with other treatments. Although 95% confidence ellipses overlapped, their centroids followed a clear gradient (control $\rightarrow$ red soil mix/MMC $\rightarrow$ peat moss/fertilizer) on PC1, aligning with tabled contrasts (e.g., higher plant N in peat moss during June and multi-trait improvements in July).

TABLE 4 Monthly survival rates (%) of *Avicennia marina* under control and peat moss treatments at rahimah with tide cycle context.

Month	Tide conditions summary	Control survival (%)	Peat moss survival (%)
May	13 high tides (3 > 1.5 m; 10 between 1.0 and 1.5 m)	72	94
June	10 high tides (all between 1.0 and 1.5 m)	57	91
July	21 high tides (6 > 1.5 m; 15 between 1.0 and 1.5 m)	20	81

High tides were classified based on water level relative to mean sea level (MSL), with values > 1.5 m defined as very high tides and those between 1.0 and 1.5 m defined as high tides.



3.5.2 Rahimah

At Rahimah, treatment separation was again driven by PC1 (64.0%), which loaded positively on survival, plant N, SPAD and chlorophyll; PC2 (19.7%) captured height (Figure 8). The peat moss cluster was distinctly right-shifted versus control, indicating superior physiological status and survival across the season. This multivariate separation mirrors univariate findings: higher SPAD and chlorophyll in April and markedly higher survival in June–July for peat moss compared with control. Height contributed little to between-group separation (mainly PC2 dispersion), reinforcing that physiological quality and survival - rather than stature - explained the treatment differences at this site.

Overall, across both sites, the dominant multivariate gradient (PC1) reflects photosynthetic/leaf N status (SPAD, chlorophyll, plant N) and, at Rahimah, survival. Treatments that enhanced these traits (peat moss, and to a lesser extent urea fertilizer at

QR) clustered at the high-PC1 extreme, while control clustered at the low-PC1 end. Ellipse overlap indicates some month-to-month variability, although the centroid shifts provide consistent evidence that peat moss improved the overall physiological profile (and survival at Rahimah), in agreement with the hypothesis and the reported significance tests.

4 Discussion

Mangrove ecosystems, particularly *Avicennia marina*, along Saudi Arabia’s eastern coast provide critical ecological functions, including shoreline stabilization, carbon sequestration, and biodiversity support. They serve as nature-based solutions for climate mitigation and coastal resilience (Shaltout et al., 2021; Macreadie et al., 2021; Alsumaiti and Shahid, 2019; Chang et al.,

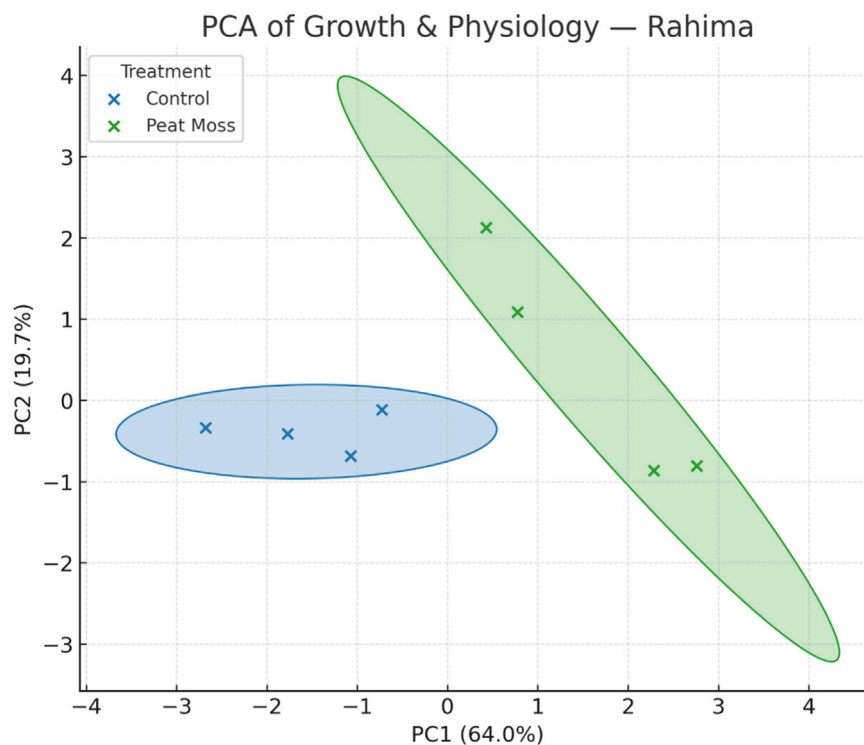


FIGURE 8

Principal component analysis (PC1–PC2) of monthly survival, height, plant N, SPAD, and chlorophyll for *Avicennia marina* seedlings at Rahimah. Each point is a Treatment × Month mean of surviving seedlings (variables standardized); $n = 8$ points across two treatments (control, peat moss). Shaded polygons are 95% confidence ellipses. PC1 = 64.0%, PC2 = 19.7% of total variance. The peat moss cluster is clearly right-shifted versus control, consistent with higher physiological metrics and improved survival later in the season.

2020; Al-Nafisi et al., 2009). However, restoration in arid and hypersaline environments remains challenging due to extreme abiotic stressors such as high salinity, nutrient-poor soils, freshwater scarcity, and intense solar radiation (Shaltout et al., 2021; Macreadie et al., 2021; Alsumaiti and Shahid, 2019). Soil organic matter is central to improving nutrient availability and soil stability, as demonstrated by earlier studies (Pribyl, 2010; Post and Kwon, 2000; Ali et al., 2009). Physiological responses of mangroves to salinity stress were first systematically characterized by Ball (2002), providing foundational knowledge for restoration research. High salinity reduces photosynthesis and water-use efficiency, although genetic variation within *A. marina* provides some resilience (Ball et al., 1988; Mohammadizadeh et al., 2009). Stressors such as high irradiance and temperature further exacerbate these challenges by inducing photoinhibition and reducing seedling survival (Martin et al., 2010; Lovelock et al., 2009; Mohammadizadeh et al., 2009). The July mortality pulse at QR is consistent with a seasonal stress window in hyper-arid sabkha systems, where extreme heat and evaporative demand can rapidly increase near-surface salinity and exacerbate physiological stress in recently established seedlings under managed (pumped) hydrology. In contrast, RH benefits from regular tidal exchange that moderates salt accumulation and maintains intertidal hydroperiod conditions, which likely reduces the magnitude of abrupt mortality events. These observations reinforce that hydrology (natural tidal exchange versus engineered inundation) is a primary determinant of survival stability and project permanence.

Field experiments highlight the potential of soil amendments in mitigating these stressors. In Iran, red clay improved water retention and seedling growth (Ghasemi et al., 2010; Ghasemi et al., 2012), while in China, red soil mixed with perlite enhanced water-holding capacity for halophytes (Lu et al., 2005). Outcomes were strongly site-specific: tidal flushing at Rahimah favored peat moss, while Qurayyah's inland soils responded moderately to red soil (Ball, 2002; Ghasemi et al., 2010; Lu et al., 2005). These findings corroborate regional studies stressing the importance of tailored soil management in arid mangrove restoration (Bhat and Suleiman, 2004; Bhat et al., 2004; Almahasheer et al., 2013; Almahasheer, 2021). Nutrient constraints, especially nitrogen and phosphorus, further limit *A. marina* productivity in the Red Sea and Arabian Gulf (Almahasheer, et al., 2016). Fertilization trials in Saudi Arabia and India show that balanced NPK additions improve growth, but overuse risks osmotic stress and microbial imbalance (Saintilan, 2003; Osman and Abohassan, 2010; Kumar et al., 2011; Romero et al., 2012; Hsiao et al., 2024). Microbial inoculants, particularly mycorrhiza, enhance nutrient cycling and mitigate salinity stress, with Gulf nursery studies demonstrating improved root–soil nutrient exchange (Al-Guwaiz et al., 2021; Alkaabi et al., 2022; Zeng et al., 2025).

Organic amendments, including peat moss, mycorrhiza, and red soil, consistently enhanced seedling survival and physiological performance by improving water retention, nutrient availability, and salinity buffering (Dharmayasa et al., 2025; Dhawi, 2025; El-Tarabily et al., 2021; Sulistiono et al., 2024; Chang et al., 2020; Abou

Seedo et al., 2017). Nevertheless, variability in field conditions, such as algal blooms, stagnant water, and irregular irrigation, created inconsistencies, as observed in global and regional studies (Erftemeijer et al., 2017; Abou Seedo et al., 2017; Abroguena et al., 2022; Erftemeijer et al., 2020; Xiao et al., 2022; Mousavi et al., 2024). Meteorological extremes also shaped restoration outcomes. At Qurayyah, seedling survival declined sharply after June, correlating negatively with rising air temperatures, declining humidity, wind stress, and solar radiation, while positively linked to soil moisture and reduced salinity, confirming the buffering role of amendments (Ball, 2002; Ball et al., 1988; Guo et al., 2018; Basyuni et al., 2014; Abroguena et al., 2022). In contrast, Rahimah's tidal influence supported higher survival under peat moss. Red soil outcomes varied with site hydrology and structure, aligning with evidence from China and Iran (Lu et al., 2005; Ghasemi et al., 2010; Ghasemi et al., 2012). Organic amendments broadly mitigated heat and desiccation stress, which are critical constraints in sabkha and coastal flat environments (Martin et al., 2010; Lovelock et al., 2009).

Sustainable alternatives to peat moss are increasingly important due to concerns over unsustainable extraction. Compost and biochar derived from date palm residues improve soil fertility and water retention in arid regions (El Janati et al., 2023; Kavvadias et al., 2024). These align with circular-economy principles and offer viable substitutes. Locally sourced materials, including composted date palm residues, coconut coir, and Al-Ahssa red clay, further enhance feasibility (El Janati et al., 2023; Kavvadias et al., 2024). Recent evidence confirms that organic amendments and artificial soil elevation not only improve restoration outcomes but also enhance blue carbon storage, integrating mangrove rehabilitation into global carbon accounting frameworks (Corona-Salto et al., 2024; Gijssman et al., 2024; Kimera et al., 2024). Moreover, hydrological classification tools and tidal management strategies are critical to maximize restoration performance (Van Loon et al., 2016; Jiang et al., 2019; Alrubaye et al., 2023; Al-Zewar et al., 2023). Soil carbon evaluation using the loss-on-ignition method remains central to restoration assessments (Ball, 2002). Kuwaiti studies highlight that soil classification and tailored management are key for successful establishment (Bhat and Suleiman, 2004; Bhat et al., 2004). Despite the demonstrated benefits of peat moss and mycorrhiza, sharp summer declines confirm that no single amendment fully counters combined stressors of heat, salinity, irradiance, and hydrological extremes. A holistic restoration framework for Gulf mangroves should therefore integrate sustainable organic amendments (e.g., agricultural waste), nursery-based acclimation with salt-gradient irrigation and staged light exposure, coupled with hydrological management and continuous environmental monitoring. Together, these measures strengthen seedling establishment, build soil carbon stocks, and support long-term ecosystem resilience under accelerating climate pressures (Motamedi et al., 2014; Jiang et al., 2019; Alrubaye et al., 2023; Al-Zewar et al., 2023; Mousavi et al., 2024).

While our study relied on integrative physiological indicators such as chlorophyll content and foliar nitrogen to assess salinity impacts on plant performance and survival, we acknowledge that more specific biomarkers of salinity stress such as proline

accumulation as an osmoprotectant, enhanced activities of antioxidant enzymes (e.g., superoxide dismutase, catalase, and ascorbate peroxidase) to mitigate oxidative damage, maintenance of favorable Na^+/K^+ ratios through ion compartmentation, and upregulation of molecular markers (e.g., SOS1 and NHX1 genes), have been reported in *A. marina* and could provide additional mechanistic insights (Jithesh et al., 2006; Kavitha et al., 2008; Patel et al., 2010; Natarajan et al., 2021). A key limitation of this study is that we did not directly quantify salinity-stress physiology (ionic, osmotic, and oxidative responses). In the pilot phase, we intentionally relied on non-invasive measurements (survival, height, SPAD/chlorophyll, visual health) to minimize disturbance and avoid harming the limited number of living plants. For future work, we recommend incorporating a targeted biomarker panel to confirm salinity stress: Na^+/K^+ ratios, proline (for osmotic adjustment), MDA (for lipid peroxidation), antioxidant enzymes (SOD, CAT, POD/APX), chlorophyll fluorescence (e.g., Fv/Fm), and water potential. These metrics would directly link hydrological/salinity conditions to physiological stress pathways and strengthen causal attribution. Furthermore, treatments were not fully factorial, and co-application (combination) effects were not directly tested; therefore, interaction effects (synergy or redundancy) among organic inputs, (MMC), and nutrient additions remain unresolved and should be quantified in a targeted factorial experiment. This study was conducted as a replicated pilot across strongly contrasting hydrological settings, so the field layout prioritized operational feasibility. Another key limitation is potential spatial confounding (pseudoreplication), because treatments were not fully randomized (QR used repeating row blocks; RH used alternating rows), meaning treatment effects may be partly confounded with row position and underlying spatial gradients (e.g., micro-topography, salinity/moisture, irrigation distribution). We therefore interpret treatment differences as field-evidence signals and focus on consistency across replicated rows and months. Future work should employ randomized/blocked designs aligned to dominant gradients, while retaining row/block identifiers (plus elevation and porewater salinity where feasible) to support mixed-effects models (e.g., logistic mixed models for survival and linear mixed models for continuous traits), thereby improving inference while remaining practical in sabkha/intertidal conditions.

In summary, this study demonstrates that while *A. marina* possesses remarkable adaptations to withstand the harsh conditions of the Arabian Gulf, restoration success is highly dependent on targeted soil management and site-specific strategies. Peat moss consistently enhanced soil carbon accumulation and seedling survival across both coastal and inland sites, while red soil and microbial amendments offered complementary benefits under certain conditions. Nevertheless, seasonal extremes and field variability underscore the need for integrated approaches that combine sustainable organic amendments, hydrological management, and adaptive nursery practices. Looking forward, adopting locally sourced and circular-economy amendments such as date palm compost and biochar can reduce reliance on unsustainable materials, while simultaneously enhancing carbon sequestration and ecosystem resilience. These findings contribute to advancing nature-based solutions for coastal restoration in arid, hypersaline regions, aligning directly with Saudi Vision 2030 and global climate mitigation efforts.

5 Conclusion

This study demonstrates the efficacy of organic soil amendments particularly peat moss, mycorrhiza, and red soil in enhancing the survival, growth, and physiological performance of *A. marina* seedlings under the arid, hypersaline conditions of Saudi Arabia's eastern coast. At Qurayyah, peat moss and red soil not only improved foliar nitrogen uptake and photosynthetic efficiency but also significantly enriched soil organic matter. At Rahimah, peat moss increased survival more than four-fold compared to the Control, highlighting its effectiveness in buffering seedlings against climatic and edaphic stressors through improved soil moisture retention and salinity mitigation.

These findings emphasize that successful mangrove restoration in Gulf sabkhas requires more than soil amendments alone. Micro-site factors such as tidal proximity, elevation, and soil moisture proved critical to establishment, while extreme summer stressors underscored the need for complementary measures. Nursery-based acclimation to sunlight, salt-gradient conditioning, elevation-specific planting, temporary shading, and supplemental freshwater emerge as essential strategies to enhance long-term resilience.

A forward-looking framework for mangrove restoration in the Gulf region should integrate **organic amendments**, precise hydrological and spatial planning, nursery acclimation strategies, and long-term monitoring to maximize success in these challenging arid environments. Future research priorities include exploring synergies among amendments and microbial inoculants, characterizing microbial community dynamics (particularly in response to multi-microbial consortia), and evaluating long-term carbon sequestration and ecosystem resilience. In particular, subsequent studies would benefit from comprehensive microbiological assessments, such as quantification and functional profiling of bacterial (*Bacillus* spp.), non-mycorrhizal fungal (*Trichoderma* spp.), and other components to elucidate the individual and interactive contributions of microbes within commercial consortia like Mikro-Myco®. Collectively, these integrated approaches can establish mangrove restoration as a pivotal element of sustainable coastal management, blue carbon initiatives, and climate adaptation in Saudi Arabia and analogous arid coastal regions globally.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

FD: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review and editing. AG: Data curation, Investigation, Methodology, Resources, Validation, Visualization, Writing – review and editing. OA: Data curation, Methodology, Project administration, Validation, Writing – review and editing. BA: Data curation,

Investigation, Resources, Validation, Writing – review and editing. RZ: Investigation, Methodology, Resources, Validation, Writing – review and editing. GA: Data curation, Investigation, Resources, Visualization, Writing – review and editing. NA: Data curation, Methodology, Resources, Validation, Writing – review and editing. JA: Conceptualization, Funding acquisition, Investigation, Resources, Supervision, Validation, Writing – review and editing. CC: Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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