Baseline Ecological Assessment of Mangrove (*Avicennia marina*) in Al Bidyah, Fujairah, United Arab Emirates

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Abstract- This study provides a baseline ecological assessment of a planted mangrove (*Avicennia marina*) stand established in Al Bidyah, Fujairah, United Arab Emirates (UAE). The site, planted in 2018 with approximately 2,500 seedlings, represents the first documented mangrove restoration effort in the Emirate. Field surveys conducted from 2018 to 2024 evaluated seedling survival, growth performance, soil properties, reproductive phenology, and associated faunal communities.

Findings indicate that *Avicennia marina* can successfully establish and reproduce on Fujairah's shallow, sandy, and rocky coastal substrates; however, growth was constrained by limited soil depth and tidal inundation. Seedling survival declined sharply from 98% in 2018 to 28% by 2020, after which it stabilized through 2024, while seedlings rooted in soils less than 6 cm deep exhibited reduced height, poor vigor, or complete mortality. Despite these constraints, reproductive activity—including flowering and propagule production—confirmed the stand's capacity for natural regeneration. Pre-existing faunal groups, particularly crabs, mollusks, and gastropods, contributed to nutrient cycling and early habitat development.

This assessment provides essential baseline data for future monitoring, restoration planning, and blue carbon initiatives in the UAE. The results highlight the potential of mangrove restoration to enhance coastal resilience, support biodiversity, and contribute to long-term ecological sustainability in arid coastal environments.

Index Terms- mangrove restoration, *Avicennia marina*, United Arab Emirates, coastal ecology, seedling survival

I. Introduction

Mangroves, locally known as "Al Qurm," are halophyte plants that require saline conditions for growth and cannot persist in freshwater (Wang et al., 2011). These salt-tolerant trees and shrubs thrive in harsh coastal environments, tolerating wide salinity ranges as well as waterlogged and anaerobic conditions. Although mangrove forests cover only about 8% of the world's coastlines (World Resources Institute, 2000), they play a disproportionately important ecological role (Suratman, 2008) and are widely recognized as among the most productive ecosystems globally (Trisanti et al., 2021).

This productivity supports an array of ecosystem goods and services, including provisioning, regulating, supporting, and cultural functions (Van Lavieren et al., 2018). Mangrove habitats sustain local livelihoods by providing fish, shrimp, crabs, and mollusks, along with timber, firewood, and charcoal (Suratman, 2008). Additional products include fruits, honey, pulp, tannin (Hamilton & Snedaker, 1984), and traditional medicines (Bandaranayake, 1998). Beyond provisioning services, mangroves play a critical ecological role by protecting coastlines from storms, waves, and tidal surges, thereby mitigating erosion and flooding (Othman, 1994).

The genus *Avicennia* (Acanthaceae), named after Avicenna or Ibn Sina (Connect with Nature, EAD-WWF), comprises eight species, of which *Avicennia marina* (Forssk.) Vierh — the grey or white mangrove — is the only species native to the UAE (Friis & Killilea, 2023). This species grows along estuaries, sheltered bays, and creeks and is characteristic of tidal zones, muddy inlets, and shallow lagoons (IUCN, 2023). *A. marina* is highly tolerant of elevated temperatures and salinity; although it is considered "notoriously tolerant," its growth improves under lower salinity conditions. Mature trees may reach up to 8 m in height, though individuals commonly attain 4–5 m. Flowering typically occurs between May and June, with almond-shaped, pale green fruits developing from September. The species provides habitats for diverse fauna, including kingfishers, fish, crustaceans, and various bird species, and is associated with green algae of the genus *Enteromorpha* (IUCN, 2023).

Mangroves are recognized as highly effective nature-based solutions for climate mitigation due to their high carbon sequestration capacity. In the UAE, mangroves cover approximately 183 km², comprising sixty million trees capable of sequestering an estimated 43,000 tons of carbon dioxide (CO_2) annually (Al Ali et al., 2023). Their carbon sequestration rates often exceed those of tropical rainforests. Together with tidal marshes and seagrasses, mangroves are classified as blue carbon ecosystems due to their ability to store substantial amounts of carbon over extended periods, regulate greenhouse gas emissions, and mitigate atmospheric CO_2 levels (Choudhary et al., 2024).

Despite their ecological and socioeconomic importance, mangrove ecosystems are increasingly threatened by urban development, pollution, aquaculture expansion, and tourism. These pressures diminish key ecosystem services, including coastal protection, fisheries, and carbon sequestration. Establishing baseline assessments of planted mangrove stands is therefore essential for tracking growth, survival, soil conditions, ecological functions, and carbon storage potential. Such data underpin restoration planning, long-term monitoring programs, and sustainable management strategies for conserving coastal habitats.

In this context, the present study provides the first baseline assessment of a mangrove stand established in Al Bidyah, Fujairah, UAE. It evaluates seedling survival, growth performance, soil characteristics, reproductive phenology, and associated biotic communities. This assessment is intended to inform future restoration efforts, enhance ecosystem service delivery, and strengthen the carbon potential of mangroves in the region.

II. Mangrove Distribution

2.1 Mangrove Global Distribution

Mangroves are critical coastal ecosystems distributed across tropical and subtropical regions worldwide. The first global assessment by the Food and Agriculture Organization (FAO) in 1980, as part of the Tropical Forest Resource Assessment initiatives, estimated a total mangrove area of 15.6 million hectares based on data from fifty-one countries (FAO, 1981). More recent analyses from the Global Mangrove Watch (GMW v4.0), using Copernicus Sentinel-2 satellite imagery, mapped 147,256 km² of mangroves across 128 countries and territories (Leal & Spalding, 2024).

Southeast Asia contains the largest mangrove extent (49,500 km², 33.6% of the global total), followed by West and Central Africa (22,802 km², 15.5%), Northern and Central America and the Caribbean (21,270 km², 14.4%), and the Middle East (358 km², 0.2%) (Leal & Spalding, 2024). Historical analyses indicate that the global mangrove area currently stands at approximately 15.2 million hectares, with Asia and Africa hosting the largest shares. Despite some reduction in the rate of loss—from 185,000 ha per year in the 1980s to 102,000 ha per year between 2000–2005—ongoing degradation remains a major concern. Approximately 3.6 million hectares (≈20%) of mangroves have been lost since 1980, primarily due to land conversion for aquaculture, agriculture, and coastal development (FAO, 2007).

Among mangrove species, *Avicennia marina* (grey mangrove) exhibits the widest biogeographic range. It is found along the east coast of Africa, throughout southwest, south, and southeast Asia, across Australia, and into northern New Zealand. In the Arabian Gulf, *A. marina* dominates, occurring along the coastlines of the UAE, Saudi Arabia, Qatar, and Iran (Haseeba et al., 2025).

2.2 Mangrove Distribution in the UAE

Within the UAE, mangroves cover an estimated 201 km², with the majority in Abu Dhabi (~176 km²), including ~11,200 ha of natural stands and ~6,400 ha of restored areas. Smaller mangrove patches exist in Sharjah and Ras Al Khaimah, with limited occurrences in other northern emirates. The emirate of Fujairah naturally lacks mangroves due to its unique geomorphological and hydrological conditions, making restoration efforts essential for establishing coastal vegetation (Moore et al., 2013; EAD, 2024).

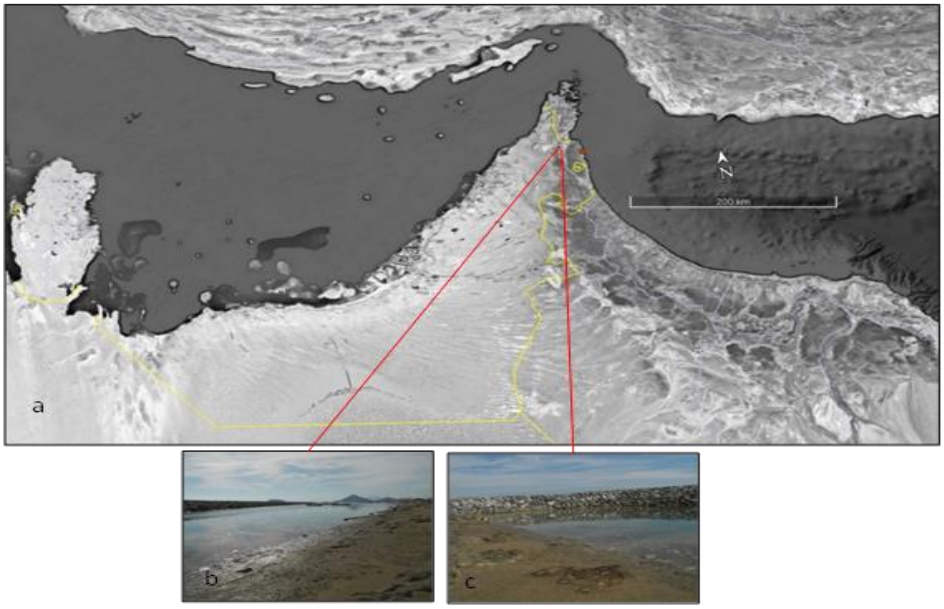
Although Fujairah does not support natural mangrove stands, restoration initiatives have been undertaken to enhance coastal ecosystems and increase green cover. In 2018, the Ministry of Climate Change and Environment (MOCCAE), in collaboration with Dibba, Al Fujairah Municipality, launched a restoration project that planted around 2,500 *A. marina* seedlings at Al Bidyah along the UAE's east coast. This initiative aimed to increase green cover and safeguard local biodiversity.

III. Methodology

The following subsections describe the methods used to evaluate mangrove establishment, growth performance, and ecological conditions at the restoration site. Procedures include seedling transplantation, growth and phenology monitoring, and assessment of water and soil physicochemical properties. Additional analyses, such as leaf morphology measurements and fauna inventories, were conducted to provide a comprehensive understanding of ecosystem development.

3.1 . Mangrove Seedling Transplantation

Mangrove seedlings aged 3–5 months were obtained from the Marine Environment Research Center (MERC) in Umm Al Quwain, UAE, and transplanted along the shoreline of Al Bidyah at the following coordinates: 25°26.825'N, 56°21.553'E and 25°26.770'N, 56°21.551'E (Figure 1). Seedlings were planted along three tidal zones—high tide, mid tide, and low tide. Seedlings measuring 6–14 cm in height were planted at the high tide line, while taller seedlings (>14 cm) were placed at the mid and low tide lines.



a. UAE Map (Google Earth Pro) b & c. photo image of the location before planting taken from 2018 (photo by:MERD-MOCCAE)

3.2. Plant Height Measurement

Seedling height was monitored during the first three years post-transplantation. During the 2024 survey, mangrove stand height was measured using either a protractor or a 360° inclinometer (Bragg, 2014).
Tree height was determined using trigonometric calculations based on a known horizontal distance. The observer, positioned on level ground aligned with the base of the tree, measured the horizontal distance (D) from the observation point to the tree using a calibrated tape measure or laser rangefinder.
Angular measurements were obtained with a 360° inclinometer featuring a fixed central hand and two independently adjustable hands. The fixed central hand was aligned with the observer's eye level to establish a horizontal reference. The upper movable hand was aligned with the tree apex to measure angle A1, and the lower hand aligned with the base to measure angle A2. Both angles were locked in consistency.
The total tree height (H) was calculated using the basic height measuring principles:

$$H = (\text{Tan}A \times D) + (\text{Tan}B \times D)$$

Where:

- **H**: Estimated total height of the tree
- **TanA**: Sine of the angle from the observer's eye level to the apex (top) of the tree
- **TanB**: Sine of the angle from the observer's eye level to the base of the tree
- **D**: Horizontal distance between the observer and the base of the tree

This approach accounts for the vertical components of both upward and downward lines of sight, providing an accurate height estimate.

3.3. Water and Soil Physicochemical Properties

Water parameters—including temperature, salinity, pH, dissolved oxygen (DO), and electrical conductivity (EC)—were measured *in situ* using a multiparameter instrument. Soil samples were collected from high and mid-tide zones, both within and outside mangrove areas, and soil depth was recorded. Samples were analyzed at the MOCCAE National Laboratory Department for pH, EC, calcium carbonate ($CaCO_3$), available copper (Cu) by DTPA, available iron (Fe) by DTPA, available manganese (Mn) by DTPA, available zinc (Zn) by DTPA, available potassium (K) by NH_4AC, available phosphorus (P) by the Olsen method, and organic matter content.

3.4. Leaf Morphology

Leaf characteristics of mangrove seedlings were assessed in 2024, six years after the initial planting in 2018, to evaluate growth and development. Seedlings were tagged according to zones: (1) seaward, (2) between seaward and middle zone, (3) middle zone, (4) between middle zone and landward zone, and (5) landward zone. For each tagged seedling, measurements included leaf length, leaf width at the top, middle, and base, and petiole length. Leaf color was also recorded to assess physiological condition and potential stress indicators. Measurements were taken using a ruler or caliper for accuracy, and leaf color was recorded visually, with reference to a standardized color chart where possible. These observations provided a quantitative assessment of morphological development over time and allowed for evaluation of the long-term growth performance and establishment success of the restored mangrove seedlings.

3.5. Phenology: Flowering and Fruiting

Monitoring of mangrove seedlings involved systematic recording of flowering and fruiting events to assess the reproductive patterns and developmental stages of the planted trees. Initial observations were conducted in 2020 to establish baseline phenology. From 2021 to 2022, monitoring was conducted quarterly, and from 2023 to 2024, observations were conducted monthly, with a particular focus on the onset of the reproductive cycle. For each tagged seedling, the timing of flowering and fruiting, duration of each event, and frequency of flower and fruit appearance were recorded. Observers also noted developmental stages, including bud formation, flower opening, fruit maturation, and fruit drop. Photographic documentation supplemented field records to verify phenophase stages and support future comparisons. This structured monitoring allowed for detailed tracking of reproductive onset, patterns, and variability across years, providing critical baseline data for evaluating the reproductive success and ecological performance of the restored mangrove seedlings.

3.6. Fauna Inventory

An inventory of fauna present in the study area was conducted to assess biodiversity and ecological interactions within mangrove zones. Observations included both aquatic and terrestrial species in areas with and without mangroves. For aquatic fauna, video and photographic surveys were conducted during the baseline assessment to document species presence. Waterproof cameras were deployed at fixed points along mangrove prop roots, tidal channels, and adjacent shallow-water areas during both high and low tides to capture variations in habitat use. Video footage and extracted still images were systematically reviewed, and species were identified based on visible morphological features, coloration, and behavior using regional identification guides. Only confirmed species were recorded, and associated habitat features such as substrate type, root density, and vegetation presence were noted. This approach provided a comprehensive baseline record of fauna present within the restored mangrove areas and adjacent habitats, serving as a reference for future monitoring and assessment of ecological recovery.

IV. Results

Since the initial planting of *Avicennia marina* seedlings at the Al Bidyah mangrove site in 2018, continuous monitoring has provided detailed insights into their growth, survival, reproductive development, and ecological interactions under arid intertidal conditions. Seedlings were established across high, mid, and low tidal zones, with initial heights ranging from 16 cm to 33 cm. Over six years, the seedlings exhibited substantial growth, reaching heights of 113–238 cm by 2024. The average height increased from 41.2 cm to 181 cm (Figure 2), reflecting both the species' resilience and the suitability of the site for mangrove restoration. Survival varied notably among tidal zones. Seedlings in the mid-tide zone exhibited the highest survival due to a combination of moderate tidal influence, adequate soil moisture, and reduced stress from barnacle and oyster attachment. In contrast, seedlings in the high- and low-tide zones experienced higher mortality, attributable to extreme tidal fluctuations, hypersalinity, shallow soils, and biofouling by marine invertebrates. Seedlings established in areas with only 1–2 cm of soil overlying rock showed markedly stunted growth, emphasizing the importance of sufficient soil depth and stability for long-term establishment.

Figure 2. Mangrove average plant height from 2018 to 2024

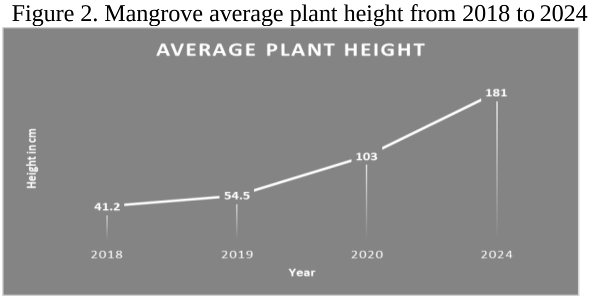


Figure 3. Mangrove survival percentage from 2018 to 2024

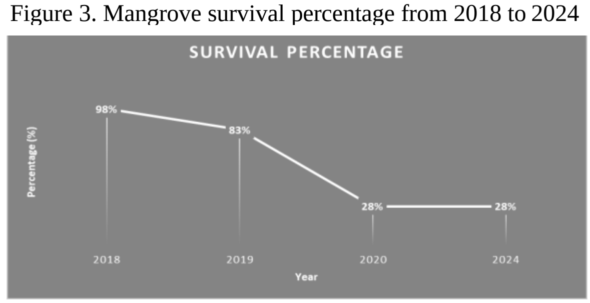


Figure 2. The line graph illustrates the average mangrove plant height growth across the same years, highlighting a steady growth trend from 2018 to 2019, followed by a sharp increase by 2024. Figure 3. Seedling survival decreased from 98% in 2018 to 28% in 2020 and remained stable through 2024.

The mangrove planting project showed substantial growth in plant height, but survival rates varied due to environmental conditions. The average height of the mangroves increased from 21.6 cm (SD = 8.23) in 2018 to 182.02 cm (SD = 52.99) in 2024, and this increase was statistically significant ($t(4.19) = -6.69$, $p = 0.002$), with an exceptionally large effect size (Cohen's d = 4.23). However, survival declined sharply from 98% in 2018 to 28% in 2020, remaining at 28% in 2024 (Figure 3). The early decline between 2018 and 2019 (98% → 83%) was due to mangroves planted in the low tide line, which were submerged during high tides for extended periods (Fig. 4, Image 1). Additionally, the growth of barnacles and blooms of seaweed, *Chaetomorpha* spp. (Fig. 4, Images b & c), further limited light, space, and oxygen availability, contributing to mortality. While fouling by barnacles can potentially affect seedlings, experimental studies have shown that barnacles do not necessarily have a significant negative effect on mangrove seedling growth and survival, with other factors such as algae, seagrass, sediment smothering, and environmental stress often having stronger influences (Saturnanatpan & Keough, 1999). By 2020, additional stress from soil loss, as soil depth decreased from 16.2 cm in 2019 to 12.73 cm in 2024, reduced root stability and made plants more prone to uprooting, explaining the mass die-off (Fig. 4, Image d). The mangroves in the low tide line did not survive, while those planted in more stable zones continued to grow robustly. Overall, the surviving mangroves exhibited dramatic and meaningful height growth, demonstrating that plant growth was highly dependent on planting location, soil stability, and environmental conditions.

Figure 4. The images above illustrate several factors that may have contributed to mangrove seedling mortality: (a) newly transplanted seedlings submerged underwater during high tide; (b & c) dense green algal mat covering most seedlings during low tide; and (d) shallow soil and erosion exposing roots, causing seedlings to lose anchorage.

Environmental conditions were a major determinant of both growth and survival. The UAE experiences extreme summer temperatures reaching 50 °C, with winter temperatures ranging from 16 °C to 24 °C, limiting enzymatic activity and constraining water transport. Tidal fluctuations produced variable salinity, measured at 38.85 ppt on May 27, 2024, which imposed osmotic stress and influenced nutrient uptake. Soil characteristics further affected seedling performance. Mid-tide zones had higher organic matter content (5.69%), sufficient potassium levels (515 mg/kg), and moderate alkalinity (pH 8.1), creating favorable conditions for root development and nutrient acquisition (Figure 5). Shallow or rocky soils in high- and low-tide zones restricted root anchorage and contributed to lower survival rates. These results underscore the critical role of tidal position, soil depth, nutrient availability, and water quality in determining the establishment success of *A. marina* under arid intertidal conditions, consistent with global observations of site-specific constraints on mangrove growth and resilience (Naidoo, 2006; Ellison, 2014).

Figure 5 Over the seven-year period, tree height shows a steady increase while dissolved oxygen exhibits a continuous decline. Temperature and salinity fluctuate slightly, and pH gradually rises, suggesting that tree growth is positively associated with increasing pH despite minor environmental variation.

Leaf morphology reflected adaptations to the harsh arid and saline environment. Leaf length ranged from 4.2 cm to 10.4 cm, width from 0.6 cm at the base to 4.5 cm at the midsection, and petiole lengths ranged from 0.3 cm to 0.8 cm. larger leaves exhibited broader midsections, whereas smaller leaves remained narrow, minimizing water loss while maintaining adequate photosynthetic capacity. These morphological traits, coupled with sustained growth over time, suggest that *A. marina* seedlings can effectively adjust their structure to cope with elevated temperatures, intense sunlight, and salinity stress. Based on the formula of Cain and DeOlivereira-Castro (1959), leaf area was computed as:

$$\text{Leaf area} = 2/3 \times (L \times W)$$

Where:

- **L:** Full length of the leaf
- **W:** Width of the leaf at its widest portion

Mangrove leaf morphological traits varied noticeably across the sampled zones, indicating a strong influence of planting zone on leaf development. Mean leaf length ranged from 4.83 cm in Zone 2 to 8.50 cm in Zone 5, showing an overall increasing trend toward higher-numbered zones. Similarly, leaf width measured at the middle portion increased from 2.20 cm in Zone 1 to 3.87 cm in Zone 5. Leaf area followed the same pattern, with the lowest mean value recorded in Zone 2 (7.49 cm^2) and the highest in Zone 5 (22.83 cm^2). These trends suggest that leaf size increased along the zonation gradient represented by the zones.

Spearman's correlation analysis supported these observations, revealing significant positive relationships between planting zone and leaf morphological traits. Leaf length was significantly correlated with zone ($p \leq 0.05$), while leaf width showed a strong positive correlation ($p = 0.00048$, $r^2 = 0.6205$). Leaf area was also significantly correlated with zone ($p = 0.006765$, $r^2 = 0.443$). These results indicate that increases in leaf size are strongly associated with zonation (Figure 6).

The observed increase in leaf length, width, and area across zones may reflect spatial variation in environmental conditions affecting mangrove growth. Differences in tidal influence, salinity exposure, and hydrodynamic stress across zones can directly affect leaf expansion and overall plant vigor. Elevated salinity, for example, can increase stomatal density, resulting in reduced leaf expansion as an adaptive response to osmotic stress (Peel et al., 2017).

These patterns are consistent with the findings of Casilac Jr. et al. (2018), who reported that leaf size indices in *Rhizophora apiculata* decreased from landward to seaward zones, except for leaf thickness. They observed the highest leaf length in the landward zone and the highest leaf width and leaf area in the middle zone, attributing these patterns to environmental stressors such as salinity, tidal inundation, and wind exposure. In contrast, our data show the largest leaf dimensions in Zone 5, suggesting that site-specific conditions at our study area may favor greater leaf expansion in that zone despite similar environmental gradients.

Although some within-zone variability was observed, the consistency between the descriptive leaf size indices and the Spearman correlation analysis strengthens the conclusion that zonation plays a key role in shaping mangrove leaf morphology. Overall, these findings indicate that leaf size traits are sensitive indicators of environmental variation across mangrove zones, while also highlighting local differences that may modulate general zonation trends.

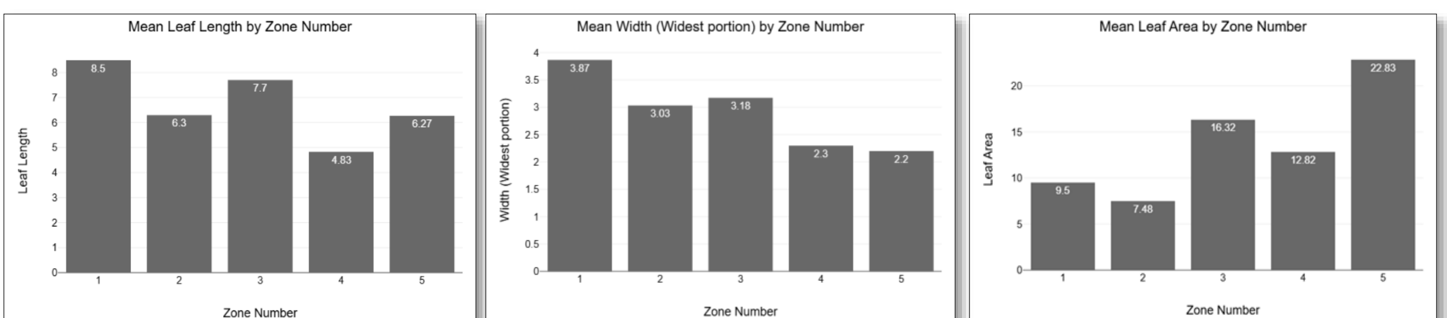


Figure 6. Mean leaf length, mean leaf width (widest portion), and mean leaf area across planting zones. Leaf length and area show an increasing trend with zone number, while leaf width varies inconsistently.

The environmental conditions corresponded with larger, dark green leaves, indicating optimal growth, minimal stress, and higher reproductive potential. Trees positioned in mid-site areas with moderate soil depth and intermediate oyster presence displayed mixed leaf colors from light to dark green and moderate leaf sizes. This suggests that moderate environmental conditions supported growth while imposing some physiological stress. In contrast, trees located closest to the seawall on shallow, stony soils with high oyster colonization exhibited smaller leaves with lighter colors ranging from yellow to light green. The combination of high salinity, limited soil depth, and intense biotic competition constrained vegetative growth and could negatively impact reproductive morphology and output.

Overall, these observations highlight the critical role of microhabitat factors—including soil depth, proximity to seawall or inlet, salinity, and oyster colonization—in shaping leaf morphology, tree development, and potential reproductive success of *Avicennia marina*. These findings correspond closely with the observed tree height data from 2018–2024 and environmental parameters such as temperature, salinity, pH, and dissolved oxygen, further emphasizing that healthier trees with larger, darker leaves are associated with more favorable environmental conditions and are better positioned to support robust flowering and seed production, whereas trees under higher environmental and biotic stress exhibit morphological indicators of reduced growth and reproductive capacity.

Reproductive activity commenced approximately two years after planting, with 40–50% of surviving seedlings producing flowers during the preliminary stages (Fig 7, Image a). Flower bud formation occurred between January and February(Fig 7, Image b), matured flowers were observed during the months of May to June(Fig 7, Image c) and some seeds maturing by June and July till the month of August (Fig 7, Image d). By 2024, reproductive activity had expanded to 90–95% of the stand, demonstrating that the restored population had achieved reproductive maturity and could sustain natural regeneration. The observed phenology aligns with the typical reproductive season of *A. marina* in arid regions, indicating that the restored population follows natural reproductive timing despite environmental stressors. Cooler winter temperatures supported flowering initiation, while the seed maturation coincided with rising summer temperatures. Seedlings in mid-tide zones, which experienced deeper soils, moderate salinity, and higher nutrient availability, exhibited higher reproductive success than those in high- or low-tide zones, underscoring the influence of environmental conditions on reproductive output.

Figure 7: Different stages of the reproductive cycle of mangroves planted in Al Bidyah: (a) flowering stage observed two years after transplanting; (b) flower bud formation recorded in succeeding years during January–February; (c) mature flowers recorded during May–June; and (d) mature mangrove seeds observed toward the end of the reproductive cycle during July–August.

By 2024, the restored mangroves at Al Bidyah supported a diverse and active faunal community, demonstrating the ecological functionality of the restored habitat. Across five sampling dates, seventeen species from multiple families were recorded, together with additional observations of key intertidal and terrestrial fauna. *Jarbua terapon* (*Terrapon jarbua*), rock oyster (*Saccostrea cuccullata*), and the pearl oyster (*Pinctada* spp.) were consistently observed, indicating high site fidelity, while other species such as common silver biddy (*Gerres oyena*), two-bar sea bream (*Acanthopagrus bifasciatus*), black-spot snapper (*Lutjanus fulviflamma*), spotted whip-tail stingray (*Himantura uarnak*), gobies (Gobiidae), swimming crabs(*Portunus pelagicus*), and a range of intertidal organisms—including mangrove snails, bivalves, and sea slugs—appeared intermittently, reflecting natural temporal fluctuations in community composition. Crab burrows and blue swimming crabs contributed to sediment turnover and nutrient cycling, while hermit crabs processed detrital material, enhancing decomposition and nutrient redistribution. Mollusks such as oysters and mud creepers colonized mangrove roots and sediments, stabilizing substrate, and adding structural complexity that supports additional fauna. Fish larvae were regularly observed near mangrove prop roots, indicating the functionality of the restored site as a nursery habitat. Green turtles were recorded foraging on algae and fallen mangrove propagules, linking the restored mangroves to adjacent marine food webs, and supporting higher trophic levels. Terrestrial insects, including butterflies and the devil's flower mantis (*Blepharopsis mendica*), were observed on vegetation,

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demonstrating connectivity between the mangroves, and surrounding terrestrial ecosystems. Collectively, these findings highlight a dynamic and multi-trophic ecosystem where both aquatic and terrestrial biodiversity benefit from the restored mangrove habitat.

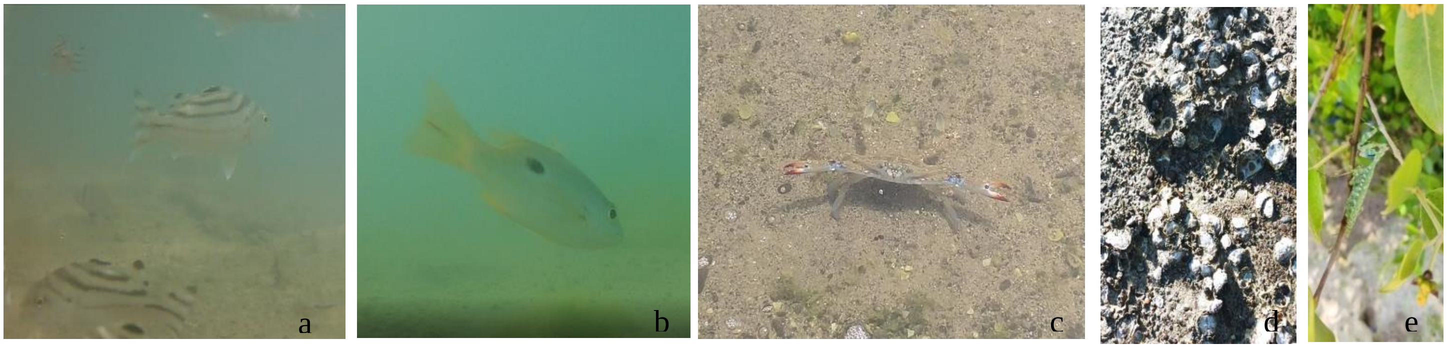

Figure 8. The images above show several mangrove-associated faunas seen in Al Bidyah: (a & b) juveniles of *Teraponidae* and *Lutjanidae*;(c) blue swimmer crabs; (d) oysters that were already present before the mangrove transplanting; and (3) a praying mantis species, considered a transient visitor.

Ecological interactions between fauna and mangroves were closely tied to environmental and habitat quality. Mid-tide zones, characterized by higher seedling survival, deeper soils, and denser canopy structure, supported the greatest diversity and abundance of faunal activity. These observations highlight the role of *A. marina* not only in providing structural habitat and stabilizing sediment but also in promoting nutrient cycling and supporting a wide range of organisms across multiple trophic levels. Overall, the Al Bidyah mangrove restoration demonstrates that *A. marina* can successfully establish, grow, reproduce, and foster complex ecological interactions even under extreme arid intertidal conditions. These findings emphasizing the importance of careful site selection, tidal monitoring, and habitat management for long-term restoration success.

V. Conclusion and Recommendations

Despite challenging climatic and aquatic conditions, *Avicennia marina* demonstrated a remarkable capacity to survive and establish at the Al Bidyah restoration site. A snapshot of water quality measured in May 2024 showed elevated temperature and salinity, slightly alkaline pH, moderate dissolved oxygen, and high conductivity, indicating a highly saline and warm environment. The presence of naturally established and newly recruited seedlings highlights the species' adaptability to these extreme conditions.

Nevertheless, soil depth emerged as a limiting factor for seedling survival, as some newly planted nursery seedlings failed to establish in areas with shallow sediments. Soil and sediment analyses across the three Bidyah sampling sites revealed no statistically significant differences, as confirmed by One-Way ANOVA ($p = 0.9318$; $F = 0.071$; $\eta^2 = 0.0067$). This uniformity can be attributed to the proximity of sampling points, which experience similar environmental conditions, reducing between-site variability. However, slight localized variations were observed, with higher organic matter (5.69%) and available potassium (515 mg/kg) at the mid-tide site with mangroves, reflecting the ecological influence of mangrove vegetation in contributing litterfall, root biomass, and enhancing sediment trapping (Table 2).

Micronutrient patterns across the three sampling zones showed subtle but ecologically meaningful differences. Available copper (0.4–0.6 mg/kg) remained uniformly low across all sites, indicating limited spatial variability, and suggesting that copper (Cu) availability is not a major differentiating factor among the zones. Available iron (Fe) showed a slight increase at the mid-tide site with mangroves (12.4 mg/kg) compared to the high-tide (10.2 mg/kg) and mid-tide without mangroves (11.6 mg/kg) sites. This modest elevation in Fe may be attributed to enhanced organic matter accumulation and reduced sediment oxidation under mangrove canopies, which tend to promote iron retention in the substrate.

Manganese (Mn) exhibited its highest concentration at the mid-tide without mangroves site (1.2 mg/kg), potentially reflecting differences in redox conditions or sediment texture between vegetated and non-vegetated areas. Potassium (K) displayed the most pronounced variation among the nutrients, with higher levels at the mid-tide mangrove site (515 mg/kg) compared to the high-tide (375.5 mg/kg) and mid-tide without mangroves (317 mg/kg) sites. This increase in K is consistent with the presence of mangrove vegetation, as mangrove litter, root turnover, and sediment trapping are known to enrich substrate potassium. Collectively, these nutrient patterns suggest that while overall sediment chemistry is broadly similar across zones, mangrove presence contributes to localized enhancement of nutrient availability, particularly for Fe and K.

The restoration of mangroves at Al Bidyah not only provides ecological benefits but also has important implications for the local community by stabilizing shorelines, improving water quality, and enhancing habitat for fish and other marine resources. Additionally, the presence of green turtles and other wildlife may promote ecotourism and environmental education initiatives, further linking conservation outcomes to community well-being.

The occurrence of green turtles within the restoration area underscores the importance of continued monitoring to determine whether their presence reflects natural foraging activity within the restored habitat or incidental bycatch. It is recommended that systematic monitoring of mangrove extent, seedling survival, and growth be maintained, alongside periodic assessment of water, soil, and sediment conditions. Furthermore, the ecological and socio-economic impacts of the restored mangroves—including contributions to local biodiversity, nutrient cycling, and ecosystem services—should be regularly evaluated to ensure the long-term success and sustainability of the restoration initiative.

Table 1. Summary of soil analysis results.

Parameter	**High Tide**	**Mid Tide w/ Mangrove**	**Mid Tide w/o Mangrove**
pH (SHJ-WSF,1)	7.80	8.10	7.90
EC (mS/cm)	25.20	40.90	38.60
$CaCO_3$ (%)	15.96	14.07	11.31
Available Cu (mg/kg)	0.4	0.6	0.6
Available Fe (mg/kg)	10.2	12.4	11.6
Available Mn (mg/kg)	0.8	0.8	1.2
Organic Matter (%)	4.82	5.69	5.0
Available K (mg/kg)	375.5	515	317

Table 2: Physicochemical properties of sediment/soil at different tidal zones in the mangrove area: high tide, mid tide with mangrove, and mid tide without mangrove. Parameters measured include pH, electrical conductivity (EC), calcium carbonate content ($CaCO_3$), available micronutrients (Cu, Fe, Mn), organic matter (OM), and available potassium (K).

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