Seedling Development Responses of *Avicennia marina* (Forssk.) Vierh. in Aquaponics, Hydroponics, and Floating Raft Systems for Optimized Mangrove Propagation

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DOI: 10.29322/IJSRP.15.11.2025.p16719
https://dx.doi.org/10.29322/IJSRP.15.11.2025.p16719

Paper Received Date: 11th October 2025
Paper Acceptance Date: 12th November 2025
Paper Publication Date: 20th November 2025

Abstract- The efficient propagation of *Avicennia marina* seedlings is vital for large-scale mangrove restoration, particularly amid increasing coastal degradation and climate change. This study evaluated the growth performance of *A. marina* seedlings over 90 days under four cultivation systems: aquaponics, hydroponics (including both drip irrigation and manual nutrient dosing), and floating raft systems. Each system received distinct nutrient sources, including aquaculture effluents from tilapia culture and organic plant-based nutrient extracts. Seedling growth was assessed through shoot height, root length, and leaf number. Statistical analysis using Welch's ANOVA and Bonferroni post hoc tests revealed highly significant differences among treatments ($p < 0.001$). Aquaponics and floating raft systems consistently produced the tallest seedlings and greatest leaf counts, indicating enhanced above-ground biomass development. In contrast, hydroponic systems promoted greater root elongation, suggesting advantages in nutrient uptake or aeration. Notably, leaf production was highest with nutrient-rich tilapia effluents, highlighting the potential of integrated aquaculture for plant propagation. Furthermore, the floating raft system's simulation of natural tidal flux supported superior foliar growth compared to the stable environmental conditions of indoor systems. These findings demonstrate that aquaponics and floating raft systems, particularly when coupled with aquaculture effluents, provide as sustainable and effective approaches to enhance mangrove seedling vigor in restoration initiatives.

Index Terms- *Avicennia marina*, mangrove propagation, aquaponics, hydroponics, nutrient sources

I. Introduction

Mangroves, particularly *Avicennia marina*, play vital ecological roles in coastal protection, carbon sequestration, and biodiversity support (Duke et al., 1998). However, increasing anthropogenic pressures and climate change threaten mangrove ecosystems worldwide, underscore the urgency of restoration efforts, such as the UAE's 100 million Mangrove Initiative (UAE MOCCAE, 2021). Conventional soil-based propagation faces challenges such as high substrate salinity and limited soil availability. These constraints have spurred interest in soilless cultivation

Aquaponics integrates fish rearing with plant cultivation, supplying nutrient-rich effluents; hydroponics allows precise nutrient delivery via drip or manual systems (Heo et al., 2024; Albadwawi et al., 2022; Dutta et al., 2023); while floating rafts emulate tidal dynamics, enhancing aeration and nutrient uptake (Budiadi et al., 2022). These systems differentially influence seedling morphological traits such as height, root length, and leaf number that determine out planting success.

This study evaluates the growth responses of *A. marina* seedlings cultivated in these soilless systems using various nutrient sources, including tilapia effluents and organic extracts. We hypothesize that systems closely replicating natural tidal environments and enhancing nutrient bioavailability particularly aquaponics and floating rafts will yield superior *A. marina* seedling growth and morphological development compared to hydroponics. Findings from this study will inform scalable, sustainable propagation methods for mangrove restoration in saline coastal regions.

I. METHODOLOGY

Study Species and Seed Collection

During the peak propagule dispersal period, mature *A. marina* propagules collected from the coastal mangroves in the UAE and selected for uniformity, with seed sizes ranging from 2 to 4cm to ensure consistency across experimental treatments. Collected propagules were washed three times with freshwater to remove debris and potential contaminants. After washing, they were then pre-treated by soaking in freshwater for 24 hours to synchronize germination and facilitate pericarp removal. This pre-treatment step was critical for enhancing germination rates and ensuring uniform seedling establishment across all cultivation systems.

Soilless culture systems

Four soilless cultivation systems were applied, as summarized in Table 1.

1. **Aquaponics**

Tilapia (*Oreochromis sp.*) fingerlings (25–30 individuals per 50L polycarbonate tank) were maintained under aerated conditions across a salinity gradient of 0 to 35 ppt. Nutrient-rich effluent from aquaponic tanks was continuously circulated (Somerville et al., 2014). *A. Marina* propagules were sown on seedling trays, without substrate, spaced one hole apart with approximately 10–15% of each propagule submerged in the water column.

2. **Hydroponics – Drip Irrigation**

To compare the effects of different nutrient delivery methods, a hydroponics–drip irrigation system was also established, where seeds were sown on propagation trays subjected to four salinity treatments (0, 10, 20 and 35 ppt), with the highest representing seawater. Each tray maintained a 2cm water level. Irrigation was through a drip system at 30mL/hr per tray, five days per week during the initial 21 days. The irrigation rate subsequently increased to 100 mL/hr, while maintaining the same frequency. Tilapia effluent water served as the nutrient source for all drip treatments. (Heo et al., 2024; Albadwawi et al., 2022; Dutta et al., 2023).

3. **Hydroponics – Manual Nutrient Dosing**

In contrast to the automated drip setup, the hydroponics–manual nutrient dosing system employed organic nutrient extracts applied by hand to evaluate how dosing frequency and substrate use affect seedling performance.

Seeds were propagated on trays containing rockwool and jiffy pot substrates under a salinity range of 15 to 20 ppt. Nutrient solutions prepared from brown seaweed and date fruit extracts were manually applied to seedlings (Shahid et al. 2017). Each extract was prepared by boiling 1kg of dried plant material in 1L of water for 1 hour (from boiling point), cooling to room temperature and diluting 1:5 with distilled water prior to application.

- For a 150mL total volume, seedlings received 30mL on day one, and again on days 7, 22, and 40; 20mL on day sixty; and 10mL on day ninety.
- For a 500mL total volume, 100mL administered on days 1, 7, 22, and 40; and 50mL on day 60 and day 90.

Seaweed was collected from the UAE coastal areas, and date fruits fallen from the tree or insect-damaged fruits. All plant materials were washed three times with freshwater (to remove debris and salt), air-dried indoors at 22.2°C under ambient light (~10 lux) for 3–5 days (to reduce moisture), and processed as described above.

4. **Floating Raft Culture (Control Reference)**

To provide a field-based comparison under natural tidal dynamics, a floating raft culture system was established as the control reference, where seedlings were placed on buoyant rafts over mangrove canal water.

Seedlings were positioned on buoyant rafts placed over natural mangrove canal water with tidal fluence. Each seedling was planted in pots containing Hydrostone medium to promote root aeration. This system served as the control reference, exposing seedlings to natural variations in temperature, salinity, light intensity, and water movement characteristic of UAE costal mangrove environments, providing a realistic environmental baseline for in Situ acclimation and growth.

5. Environmental Conditions

To ensure valid comparisons across all soilless systems, indoor cultivation systems were maintained under controlled environmental conditions optimized for seedling growth. Room temperature was regulated between 22.20ºC and 27.00ºC, providing optimal thermal conditions for halophytic metabolic activity. Relative humidity ranged from 42% to 76%, reducing water stress while limiting pathogen proliferation. Maintaining balanced humidity is particularly critical, as low humidity coupled with high salinity has been linked to reduced cold tolerance in mangrove species (Devaney et al., 2021). Light intensity was maintained at approximately 221 lux, sufficient for early-stage seedling development under controlled environments (Luna et al., 2019). A 10–12 hour of light period followed by 12–14 hours of darkness was implemented to approximate natural photoperiods and support proper circadian regulation.

In contrast, the floating raft system was exposed to ambient coastal conditions and tidal fluctuations, providing a realistic environmental baseline for in situ acclimation and growth.

Table 1. Growth Systems used for *A. marina* seedling propagation.

Culture System	Water and Nutrient Sources	Salinity Range (ppt*)	Irrigation Method	Nutrient Input	Substrate/Medium	Seed Placement & Preparation
Aquaponics	Tilapia effluent (polycarbonate tanks)	0–35 (including pure seawater, matched to drip system)	Continuous flow, oxygenated	Continuous effluent nutrients from fish	None	Seeds placed one hole apart on seedling trays; 10–15% seeds soaked in water; no substrate
Hydroponics – Drip	Tilapia effluent	0–35 (4th treatment: pure seawater)	Drip system: 30.0 mL/hr** (Days 1–21), 100.0 mL/hr (after Day 21), 5 days/week	Controlled drip irrigation using fish effluent	None	Seeds placed on propagation trays
Hydroponics – Manual Nutrient Dosing	Freshwater with seaweed/date fruit extracts	15–20	Manual dosing	Extracts from UAE seaweed and fallen/insect-bitten date fruits	Rockwool and jiffy pots	Seeds placed on propagation trays; substrate used; extract made by boiling 1 kg dried plant in 1 L water, diluted 1:5 after cooling
Floating Raft	Natural mangrove canal (tidal)	Natural salinity variation (subject to tidal fluctuations)	Passive (no active irrigation)	Natural tidal nutrient flow	Hydrostone in seedling pots	Seedlings placed on buoyant rafts over canal water

*ppt = parts per thousand; **mL/hr. = milliliters per hour
Note. The salinity range for the Aquaponics system was standardized to 0–35 ppt, encompassing pure seawater, to align with the experimental design of the Hydroponics – Drip system (Rakocy et al., 2006). This adjustment ensured comparability across systems under identical saline conditions. The Hydroponics – Manual Nutrient Dosing system retained its original salinity range of 15–20 ppt.

Data Collection

After 90 days, seedling height (cm), root length (cm), and number of leaves was recorded for 325 seedlings across the systems.

Statistical Analysis

Normality was checked using the Kolmogorov-Smirnov, Shapiro-Wilk, and Anderson-Darling tests. However, the assumption of homogeneity of variance was violated; therefore, Welch's ANOVA was applied, followed by Bonferroni-adjusted post hoc tests for pairwise comparisons. The significance level was set at $p < 0.05$.

II. RESULTS AND DISCUSSION

Results

Seedling Height

After 90 days, seedling height differed significantly among the soilless cultivation systems (Welch's ANOVA, F (3, 109.36) = 47.96, $p < 0.001$), indicating that system design, nutrient delivery, and environmental conditions influenced growth performance. Seedlings grown in the aquaponics (19.57 ± 3.65cm) and Floating Raft (20.37 ± 3.97cm) systems were significantly taller than those grown in the hydroponics drip (12.40 ± 2.13 m) and hydroponics manual nutrient dosing (15.74 ± 3.12 m) systems.

Enhanced growth in aquaponics and floating raft systems can be attributed to continuous nutrient availability and improved root aeration conditions. In aquaponics, tilapia effluent provided a consistent supply of bioavailable nutrients, complemented by oxygenated water maintained by aeration systems (Somerville et al., 2014; Heo et al., 2024; Albadwawi et al., 2022). Similarly, the floating raft exposed seedlings to tidal fluctuations and ambient mangrove canal conditions, facilitating regular oxygenation and nutrient replenishment—conditions favorable for *A. Marina* seedlings that naturally thrive in dynamic, nutrient-cycling environments.

Conversely, the hydroponics drip system provided nutrients intermittently via scheduled drip irrigation (30-100 mL/hr.), using tilapia effluent water with salinities of 0 to 35 ppt(Heo et al., 2024; Dutta et al., 2023). Despite increased drip rates over time, the discontinuous nutrient supply and lack of continuous root immersion limited nutrient uptake and shoot elongation compared to aquaponics and floating raft systems. The hydroponics manual nutrient dosing system, which used rockwool substrate and manual application of seaweed and date fruit extracts at salinities of 15–20 ppt (Shahid et al., 2017), achieved intermediate growth. Less frequent dosing likely constrained nutrient availability, though biofertilizers and plant growth promoters partially mitigated this limitation (Singh et al., 2023).

Post hoc Bonferroni tests revealed significant differences between aquaponics and hydroponics drip (mean difference = 7.17 cm, $p < 0.001$) and between floating raft and hydroponics manual nutrient dosing (mean difference = 4.63 cm, $p < 0.001$). No significant difference was found between aquaponics and floating raft ($p = 1.000$), indicating comparable shoot elongation potential between these two systems. (see Table 2).

Table 2. Pairwise Comparison of Seedling Height Across Cultivation Systems.

Comparison	Mean Diff (cm)	*p*-value	Interpretation
Aquaponics vs Hydro Drip	+7.17	<0.001	Aquaponics taller
Aquaponics vs Hydro Manual	+3.83	<0.001	Aquaponics taller
Aquaponics vs Floating Raft	-0.80	1.000	No difference
Hydro Drip vs Hydro Manual	-3.35	<0.001	Manual taller
Hydro Drip vs Floating Raft	-7.98	<0.001	Raft taller
Hydro Manual vs Floating Raft	-4.63	<0.001	Raft taller

These results highlight the importance of continuous nutrient delivery, root zone oxygenation, and environmental stability in optimizing seedling growth in soilless systems, supporting the integration of aquaponics and natural floating raft culture as effective approaches for mangrove propagation and restoration efforts (Somerville et al., 2014).

Number of Leaves

The number of leaves per seedling was significantly influenced by the cultivation system (Welch's ANOVA, $F(3, 108.6) = 89.71$, $p < 0.001$), underscoring the role of growing conditions in foliar development. Seedlings grown in the floating raft system exhibited the highest mean leaf count (5.3 ± 0.65), followed by aquaponics system (5.12 ± 1.16), while both hydroponic systems manual nutrient dosing (3.85 ± 0.8) and Drip Irrigation (3.19 ± 0.92) produced significantly fewer leaves per seedling (Table 3). These results indicate that continuous nutrient availability and natural environmental fluctuations, characteristic of floating raft and aquaponics systems, may enhance leaf initiation and expansion compared to hydroponic methods relying on intermittent nutrient delivery (Somerville et al., 2014).

Bonferroni post hoc tests confirmed significantly higher leaf counts in aquaponics and floating raft systems compared to both hydroponics manual nutrient dosing and hydroponics drip systems ($p < 0.001$). No significant difference was observed between aquaponics and floating raft systems (mean difference = -0.18, $p = 1.000$), suggesting both provide optimal conditions for foliar development in *Avicennia marina* seedlings.

Table 3. Pairwise Comparison of Number of Leaves per Seedling Across Cultivation Systems

Comparison	Mean Diff	p-value	Interpretation
Aquaponics vs Hydroponics Drip	+1.93	<0.001	Aquaponics higher
Aquaponics vs Hydroponics Manual	+1.27	<0.001	Aquaponics higher
Aquaponics vs Floating Raft	-0.18	1.000	No difference
Hydroponics Drip vs Hydro Manual	-0.66	<0.001	Manual higher
Hydroponics Drip vs Floating Raft	-2.11	<0.001	Raft higher
Hydroponics Manual vs Floating Raft	-1.45	<0.001	Raft higher

Root Length

Root length also varied across cultivation systems (Welch's ANOVA, $F(3, 111.55) = 70.86$, $p < 0.001$), reflecting the effects of nutrient delivery, irrigation method, and root zone environment on belowground development (Table 4). The Hydroponics manual nutrient dosing system produced the longest roots (20.11 ± 6.67 cm), followed by Hydroponics Drip system (18.35 ± 5.01 cm) and the floating raft system (17.11 ± 4.89 cm), while aquaponics seedlings had the shortest roots (10.38 ± 4.10 cm). The longer roots in hydroponic systems can be attributed to the rockwool substrate's high porosity and moisture retention, providing an aerated medium elongation.

Table 4. Pairwise Comparison of Root Length Across Cultivation Systems.

Comparison	Mean Diff (cm)	p-value	Interpretation
Aquaponics vs Hydroponics Drip	-7.97	<0.001	Hydro Drip taller

Aquaponics vs Hydroponics Manual	-9.73	<0.001	Hydro Manual taller
Aquaponics vs Floating Raft	-6.73	<0.001	Floating Raft taller
Hydroponics Drip vs Hydro Manual	-1.76	0.227	No significant difference
Hydroponics Drip vs Floating Raft	+1.24	1.000	No significant difference

These findings demonstrate that root elongation in *A. marina* seedlings is modulated by nutrient accessibility and oxygenation. Systems providing constant nutrient exposure (e.g., aquaponics) favor compact root systems, while those requiring active nutrient foraging (e.g., hydroponics) promote longer roots.

Discussion

Seedling Height and Shoot Growth

After 90 days, seedlings cultivated in the aquaponics and floating raft systems exhibited greater height than those grown in the Hydroponics Drip and manual nutrient dosing systems (Figure 1.). This enhanced shoot growth can be attributed to the continuous nutrient availability and improved root aeration characteristic of these systems, both seedling development responses of *Avicennia marina (Forssk.) Vierh*. in aquaponics, hydroponics, and floating raft systems for optimized mangrove propagation which contribute substantially to the successful establishment of mangrove seedlings (Albadwawi et al., 2022; Heo et al., 2024; Singh et al., 2023).The floating raft system, in particular, benefits from natural tidal fluctuations and associated environmental variability, including periodic changes in salinity and water movement. Such dynamic hydrological conditions closely simulate natural estuarine habitats, known to trigger physiological and morphological responses that promote growth in *Avicennia marina* seedlings (Budiadi et al., 2022). The interplay of these factors enhances nutrient uptake efficiency and facilitates greater shoot elongation, consistent with previous studies reporting that hydrodynamic forces improved mangrove seedling growth by influencing nutrient transport and root respiration. similarly, the aquaponics system's provision of oxygenated, nutrient-rich effluent water ensures a stable supply of essential macro- and micronutrients, promoting vigorous shoot development (Somerville et al., 2014). Collectively, these results highlight the importance of both nutrient regime and environmental simulation in optimizing early growth performance of mangrove seedlings in controlled cultivation systems. These findings are corroborated by studies demonstrating enhanced mangrove growth using hydroponic systems supplemented with organic nutrient solutions (Syakir et al., 2021).

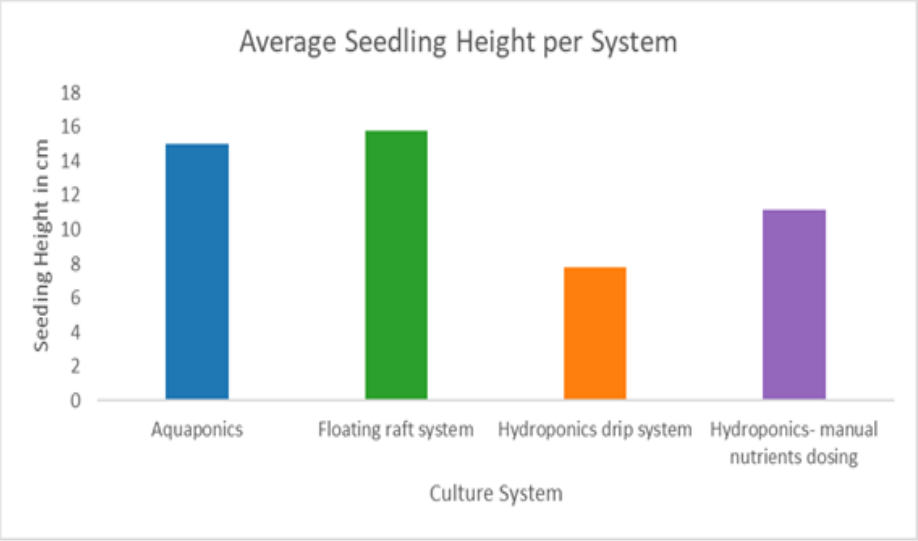

Figure 1. Seedling height after 90 days under different culture systems.
Seedlings grown in the **aquaponics** and **floating raft** culture systems exhibited the greatest average height (14.96–15.77 cm), significantly higher than those in the **hydroponics drip** (7.79 cm) and **manual nutrient dosing** (11.14 cm) systems.

Leaf Count and Environmental Conditions

The number of leaves per seedling was highest in the Floating Raft system, followed closely by the Aquaponics system, highlighting the critical influence of nutrient availability and environmental complexity on foliar growth (Figure 2). This result aligns with previous studies showing that continuous nutrient supply and dynamic environmental conditions enhance leaf expansion in mangrove seedlings (Somerville et al., 2014). In the Floating Raft system, natural tidal cycles provided periodic pulses of nutrients and dynamic salinity fluctuations factors known

to stimulate leaf production and overall plant vigor by mimicking native estuarine conditions (Budiadi et al., 2022). These fluctuating environments closely resemble the natural habitat of *Avicennia marina*, which thrives under changing salinity and nutrient availability, thereby promoting healthy leaf development.

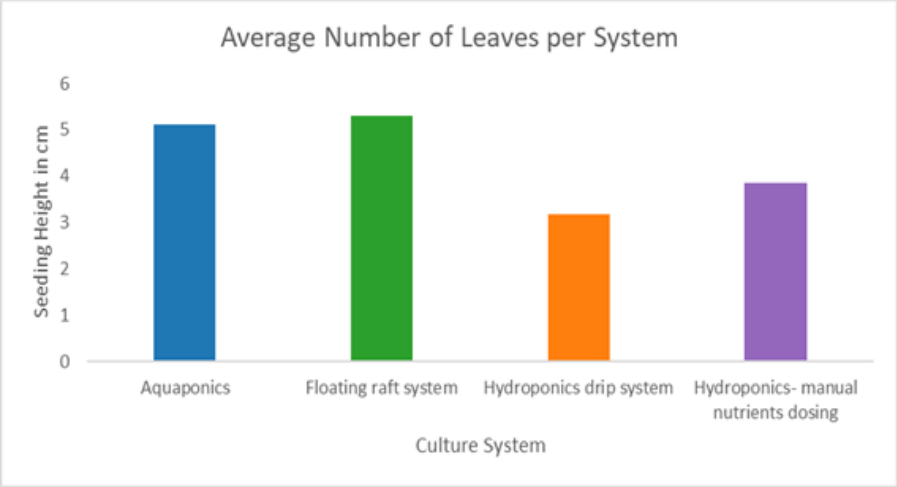

Figure 2. Average number of leaves per seedling after 90 days under different culture systems.
Seedlings grown in the floating raft system had the highest average leaf count (5.3), followed closely by the aquaponics system (5.12). seedlings in the hydroponics drip (3.19) and manual nutrient dosing (3.85) systems produced fewer leaves.

By contrast, the Hydroponics systems—operating under controlled conditions with low light intensity (approximately 221 lux) and moderate temperatures (22.2–27 °C) —exhibited lower leaf counts. Reduced light availability likely limited photosynthesis and hindered foliar expansion (Chen et al., 2023).

On the other hand, the Aquaponics system provided a continuous supply of nutrient-rich fish effluent and maintained stable environmental parameters, promoted enhanced foliar development. This outcome is consistent with previous findings that aquaponics supports plant growth synergistic nutrient cycling and consistent water quality (Rakocy et al., 2006).

Overall, these results emphasize the need to integrate nutrient dynamics and environmental variability to optimize mangrove leaf growth in soilless systems. The enhanced leaf observed in the Floating Raft and Aquaponics setups highlights the importance of environmental complexity and nutrient availability in promoting optimal foliar development key for replicating natural mangrove habitat in nursery cultivation.

Root Development and Nutrient Uptake

Root length variations among the cultivation systems reflect the influence of nutrient delivery methods and root zone oxygenation on root architecture. Seedlings grown in the Hydroponics manual nutrient dosing and drip systems exhibited the greatest root elongation, whereas those in the aquaponics system developed the shortest roots (Figure 3). This variation stems from differences in nutrient delivery methods and oxygen availability critical factors shaping root morphology (Shivani et al., 2024). In hydroponic systems, nutrient solutions are typically supplied intermittently or manually, prompting seedlings to extend their roots further to optimize nutrient foraging. This is particularly vital in saline, nutrient-poor mangrove environments where resource acquisition is challenging (Budiadi et al., 2022). Additionally, the use of substrates such as rockwool in the manual nutrient dosing system promoted root elongation by providing physical support and aeration, which is known to enhance root growth.

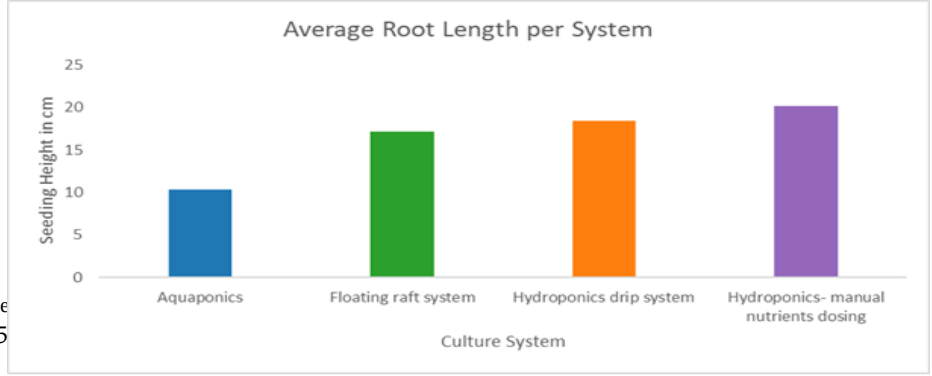

Figure 3. Average root length of mangrove seedlings after 90 days under different culture systems.

In contrast, the aquaponics system provided a continuous flow of oxygenated, nutrient-rich effluent, reducing the need for extensive root proliferation, as seedlings could readily access dissolved nutrients within a confined root zone. This nutrient-rich and well-aerated environment promoted a more compact root system, optimizing energy allocation toward shoot development. Similar findings highlighted the influence of substrate conditions and nutrient accessibility on root morphology in mangrove species (Somerville et al., 2014).

III. CONCLUSION

This study demonstrates that aquaponics and floating raft systems significantly enhance *Avicennia marina* seedling height and leaf production compared to Hydroponics. These advantages stem from continuous nutrient bioavailability through fish effluent in Aquaponics (Heo et al., 2024; Albadwawi et al., 2022) and environmental simulation via tidal fluctuations in Floating Rafts, both of which optimize seedling growth (Somerville et al., 2014). In contrast, Hydroponics systems promoted longer roots but reduced shoot and leaf development, indicating the need for refined nutrient and environmental management (Budiadi et al., 2022).

Traditional soil-based propagation often limits nutrient availability and root aeration, constraining growth (Kathiresan & Bingham, 2001). Soilless systems address these challenges by providing bioavailable nutrients and sufficient oxygenation, resulting in more vigorous seedlings.

Tilapia effluent in aquaponics offers a sustainable nutrient source that reduces chemical fertilizer dependence (Heo et al., 2024; Albadwawi et al., 2022)while floating rafts simulate natural tidal and salinity variations essential for mangrove acclimation (Budiadi et al., 2022). these approaches collectively enhance seedling quality, survival, and increased restoration success.

Scaling aquaponics and floating rafts systems can support national and global initiatives) such as the UAE's 100 million Mangrove Initiative) by offering efficient, resilient nursery propagation techniques (UAE Ministry of Climate Change and Environment, 2021). The advantages and limitations of these systems were summarized in Table 5. Optimizing propagation strategies is vital to meet global mangrove restoration demands amid environmental challenges.

Future Directions

Future work should focus on optimizing indoor hydroponic conditions particularly by increasing light intensity and refining nutrient dosing to enhance growth parameters such as leaf production and shoot elongation. Suboptimal lighting limits photosynthetic efficiency and plant development in controlled environments (Chen et al., 2023), while precise nutrient management is essential for balancing root and shoot growth (Dutta et al., 2023; Nitu et al., 2024). Defining optimal environmental thresholds tailored to *Avicennia marina's* physiological will maximize seedling performance in soilless systems.

Additionally, long-term field validation of nursery-grown seedlings is necessary. Monitoring survival, growth, and physiological responses under natural salinity gradients and tidal regimes will confirm the ecological applicability of these propagation methods (Alongi, 2015). integrating controlled environment findings within situ restoration will ensure seedlings maintain vigor and resilience after transplantation crucial for sustainable mangrove conservation amid changing coastal conditions.

Table 5. Comparative Summary of *A. marina* Nursery Systems

System	Nutrient Delivery	Root Aeration & Environment	Seedling Growth Outcomes	Advantages	Limitations
Seedling Bag + Sand (Traditional)	Nutrients limited to sand/soil substrate	Limited aeration, static environment	Moderate root and shoot growth; sometimes restricted development	Simple, low-cost, widely practiced	Nutrient limitation, poor root aeration
Aquaponics	Continuous fish effluent nutrient supply	Good aeration in water, controlled indoor conditions	High seedling height and leaf production; shorter roots due to nutrient abundance	Sustainable nutrient recycling; controlled environment	Requires aquaculture setup; system maintenance
Floating Raft	Nutrient uptake from natural tidal water	Excellent aeration and tidal fluctuation exposure	High shoot growth and leaf number; mimics natural conditions	Simulates estuarine environment; scalable	Dependent on-site conditions; environmental variability

Hydroponics (Drip & Manual Nutrient Dosing)	Nutrients delivered via controlled dosing; seaweed/date fruit extracts in manual	Indoor controlled environment; substrate-based or soilless	Longer roots but lower shoot and leaf growth	Precise nutrient control	Lower shoot/leaf growth under low light; complex dosing needed

Acknowledgment

The authors gratefully acknowledge the support of the UAE Ministry of Climate Change and Environment for their guidance, logistical assistance, and provision of essential resources. Their support was instrumental in the successful execution of this study on sustainable mangrove propagation.

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