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Enhancing acclimatization of *in vitro*-propagated turmeric (*Curcuma longa* Linn.) in soilless systems

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Abstract

Acclimatizing *in vitro*-propagated turmeric presents challenges and opportunities. This study evaluated the growth performance and survival of in vitro-propagated turmeric acclimatized in soilless systems using varying seaweed extract concentrations (0.5, 0.75, 1.0, and 1.5 mL) in a factorial completely randomized design (CRD). Aeroponic systems significantly enhanced growth parameters (plant height, stem diameter, leaf number, leaf area) compared to hydroponic systems, due to improved oxygen availability and nutrient uptake. 1.0 mL seaweed extract further optimized growth, showing the highest values for plant height, stem diameter, and leaf area. A significant interaction between acclimatization system and seaweed extract concentration was observed; aeroponics with 0.75 mL seaweed extract yielded the tallest plants and largest leaf area. Aeroponics also resulted in superior root development and significantly higher biomass accumulation than hydroponics. The highest biomass was achieved with 1.0 mL seaweed extract. A 100% survival rate across all treatments confirmed turmeric's adaptability to soilless systems. These findings highlight the synergistic benefits of aeroponics and moderate seaweed extract supplementation for optimizing *in vitro*-propagated turmeric acclimatization and growth.

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Introduction

Acclimatization is a critical phase in the propagation of *in vitro* plants, bridging the gap between controlled laboratory conditions and external cultivation environments. During tissue culture, plants are grown under optimal conditions with controlled humidity, light, and nutrients, but these environments do not prepare the plants for external stresses (Sharma *et al.,* 2023). The transition from sterile, nutrient-rich agar to open systems poses challenges, especially for plants like turmeric (*Curcuma longa* Linn.), which have fragile roots and a high susceptibility to environmental stress during early development (Rai *et al.,* 2017).

Successfully acclimatizing these plants is essential to ensure high survival rates and robust growth in subsequent cultivation phases. Traditional acclimatization methods involve transferring plants to soil or soil-based media, where they gradually adapt to the external environment. However, these methods often result in high mortality rates due to insufficient control over environmental factors, such as nutrient availability and moisture levels (Darwesh, 2015). Additionally, soil-based acclimatization is labor-intensive, prone to contamination, and often inefficient for large-scale operations (Deb and Imchen, 2010). Soilless cultivation systems, such as hydroponics and aeroponics, have gained attention for their potential to enhance plant growth and acclimatization by providing controlled environments with optimized nutrient and oxygen availability (Pomoni *et al*., 2023; Hale *et al*., 2015).

Hydroponics involves growing plants in nutrient-rich water, while aeroponics suspends plant roots in air and intermittently mists them with nutrient solutions (Hosseinzadeh *et al.,* 2017).

Both systems offer advantages over traditional soil-based cultivation, including reduced risk of soil-borne diseases, efficient nutrient utilization, and improved root zone oxygenation (Lakkireddy *et al.,* 2012). However, the comparative efficacy of these systems in enhancing the acclimatization and growth performance of *in vitro*-propagated turmeric remains underexplored. In addition to acclimatization systems, the use of biostimulants, such as seaweed extracts, has been shown to enhance plant growth and stress tolerance. Seaweed extracts are rich in bioactive compounds, including phytohormones (auxins, cytokinins, and gibberellins), trace minerals, and polysaccharides, which promote cell division, root elongation, and nutrient uptake (Mughunth *et al.,* 2024; Chaturvedi *et al.,* 2022). While the benefits of seaweed extracts have been documented for various crops, their application in conjunction with soilless systems for turmeric acclimatization has not been thoroughly investigated. Understanding the interaction between acclimatization systems and seaweed extract concentrations is essential for optimizing the growth and development of *in vitro*-propagated turmeric. This study provides insights into the synergistic effects of soilless systems and biostimulants on turmeric acclimatization. The findings contribute to the development of efficient acclimatization strategies for enhancing the productivity and quality of turmeric, thereby enhancing the survival and growth of *in vitro*-propagated turmeric plants.

Materials and methods

Plant material preparation and experimental design

In vitro-propagated turmeric plantlets were screened for size, vigor, and health. Contaminated, abnormal, or stressed plantlets were discarded. To maintain consistency, selected plantlets were at the same growth stage, measuring 4–5 cm in height with 3–4 fully expanded leaves, and prepared for acclimatization. The study used a completely randomized factorial design to evaluate the effects of seaweed extract on *in vitro* turmeric plantlet acclimatization. Four concentrations (0.5, 0.75, 1.0 and 1.5 mL) were tested, along with two acclimatization systems (hydroponic and aeroponic), each with three replicates.

Acclimatization strategies

The Kratky method, a simple and efficient passive deep-water culture system, was used for the hydroponic setup

(Lori, 2022). The system included a reservoir, net pots, growing medium, and nutrient solution. Plantlets were placed in net pots with the plant support structure, typically made from polyurethane (PU) foam materials, which held the plants in place while allowing the roots to hang freely. The nutrient solution in the reservoir initially covered the bottoms of the net pots, with pH set between 5.5–6.5 (Almeselmani, 2022) and electrical conductivity at 1.8–2.5 dS m^{-1} (Nair 2019; Ding *et al.,* 2018) to support early turmeric growth. As the water level dropped, an air gap formed to aerate the roots, promoting nutrient uptake. Regular checks ensured stable nutrient levels and pH. In the aeroponic system, plantlets were suspended in a misting chamber where nutrient solutions were delivered directly to the roots. Plantlets were anchored in net pots with roots freely dangling in the enclosed misting environment. A 12-volt water pump with a 4,163.95 L h^{-1} flow rate circulated the solution through a PVC misting network with nozzles producing a fine mist. The system operated on a programmable timer, misting for 5 minutes followed by a 30-minute pause, ensuring efficient nutrient delivery and preventing waterlogging (Tunio *et al.,* 2021).

Crop management

Proper crop care and management were carried out. Strict monitoring and frequent adjustments of the nutrient solution's pH and EC were performed to prevent root diseases and maintain system cleanliness. Temperature was also monitored and maintained at optimal levels. Additionally, misting intervals and nutrient concentrations were regularly observed to prevent clogs and ensure optimal root hydration and health.

Measurements

Plant height and stem diameter were measured, leaf count was performed manually, and leaf area was determined to assess acclimatization success in hydroponic and aeroponic systems.

Data analysis

Data analysis involved ANOVA using the Statistical Tool for Agricultural Research (STAR), with Tukey's HSD test applied to compare significant treatment means.

Results and discussion

Growth performance of acclimatized turmeric

Acclimatization system effect on growth

The growth performance of *in vitro*-propagated turmeric acclimatized under soilless systems, along with varying concentrations of seaweed extract, is presented in Table 1. The results revealed that the aeroponic system significantly enhanced all growth parameters compared to the hydroponic system. Plants grown under aeroponic conditions attained the highest plant height (135.88 mm), stem diameter (5.37 mm), number of leaves (6.25), and leaf area (926.73 cm^2), all of which were significantly greater than those recorded in hydroponics (121.29 mm, 5.14 mm, 5.91, and 861.54 cm^2, respectively). The findings demonstrate that the aeroponic system significantly enhances the acclimatization and growth performance of *in vitro*-propagated turmeric compared to the hydroponic system. This is likely due to improved oxygen availability, which facilitates better root respiration and nutrient uptake, leading to increased plant height, stem diameter, number of leaves, and leaf area. These findings align with previous studies that highlight the efficiency of aeroponics in providing optimal growth conditions for various plant species, particularly in root zone oxygenation and nutrient absorption efficiency (Lakhiar *et al.,* 2018; Khater, 2015; Ali *et al.,* 2017; Broćić *et al.,* 2021; (Li *et al.,* 2018).

Seaweed extract effect on growth

Among the varying concentrations of seaweed extract, the highest values for plant height (138.45 mm), stem diameter (5.43 mm), number of leaves (6.35), and leaf area (927.30 cm^2) were recorded at 1.00 mL seaweed extract. This concentration produced significantly taller plants and larger leaves compared to the lowest concentration (0.50 mL, B1), which resulted in the poorest growth performance (114.82 mm plant height, 5.05 mm stem diameter, 5.72 leaves, and 835.18 cm^2 leaf area). The results reveal that the application of 1.00 mL seaweed extract significantly improved turmeric growth, particularly in terms of plant height, stem thickness, and leaf area. Seaweed extracts are rich in bioactive compounds, such as auxins, cytokinins, and gibberellins, which enhance cell division, elongation, and photosynthetic activity (Mughunth *et al.*, 2024; Chatuverdi *et al.,* 2022). The findings corroborate previous research indicating that moderate concentrations of seaweed extracts can promote plant growth by improving nutrient uptake and stress resistance (Yusuf *et al.*, 2021). However, a higher concentration of 1.50 mL resulted in a slight decline in growth parameters, suggesting a potential threshold beyond which excessive seaweed extract application may cause metabolic imbalances or osmotic stress (Latique *et al.*, 2013).

Table 1. Growth performance of acclimatized turmeric

Treatments	Plant height, mm	Stem diameter, mm	Number of leaves	Leaf area, cm²
Acclimatization system				
Hydroponic	121.29b	5.14b	5.91b	861.54b
Aeroponic	135.88a	5.37a	6.25a	926.73a
Varying seaweed extract concentrations				
0.50 mL	114.82b	5.05b	5.72b	835.18b
0.75 mL	134.27a	5.28ab	6.13ab	914.92a
1.00 mL	138.45a	5.43a	6.35a	927.30a
1.50 mL	126.80ab	5.25ab	6.12ab	899.15ab
Interaction				
Hydroponic × 0.50 mL	107.93f	4.90d	5.50e	799.87f
Hydroponic × 0.75 mL	115.33ef	5.07cd	5.77de	842.90ef
Hydroponic × 1.00 mL	138.40b	5.40ab	6.30abc	917.80bc
Hydroponic × 1.50 mL	123.50cd	5.20bc	6.07bcd	885.60cde
Aeroponic × 0.50 mL	121.70de	5.20bc	5.93cd	870.50de
Aeroponic × 0.75 mL	153.20a	5.50a	6.50a	986.93a
Aeroponic × 1.00 mL	138.50b	5.47ab	6.40ab	936.80b
Aeroponic × 1.50 mL	130.10c	5.30abc	6.17abc	912.70bcd
CV%	2.14	1.86	2.28	1.78

Synergistic effects of acclimatization system and seaweed extract on growth

A significant interaction between the acclimatization system and seaweed extract concentration was observed across all growth parameters, highlighting the importance of optimizing both factors simultaneously. For plant height, the tallest plants (153.20 mm) were recorded under Aeroponic with 0.75 mL, which significantly outperformed all other treatment combinations. This suggests that moderate seaweed extract concentration combined with an aeroponic creates a synergistic effect, enhancing growth potential. Meanwhile, the shortest plants (107.93 mm) were observed in hydroponic with 0.50 mL, confirming the limited effectiveness of this treatment. In terms of stem diameter, plants under aeroponic with 0.75 mL seaweed extract exhibited the thickest stems (5.50 mm), reinforcing the superiority of aeroponic conditions. Conversely, the smallest stem diameter (4.90 mm) was recorded in hydroponic with 0.50 mL, further emphasizing the need for optimized nutrient supplementation in hydroponics. The number of leaves followed a similar trend, with the highest count (6.50 leaves) in aeroponicx0.75 mL and the lowest (5.50 leaves) in hydroponic with 0.50 mL. This indicates that turmeric plants benefit from moderate seaweed extract supplementation, particularly in aeroponic conditions. For leaf area, the largest values were again observed in aeroponic with 0.75 mL seaweed extract (986.93 cm²), followed closely by aeroponic with 1.00 mL (936.80 cm²) and aeroponic with 1.50 mL seaweed extract (912.70 cm²), signifying that aeroponic systems consistently promote superior leaf expansion. The smallest leaf area (799.87 cm²) was recorded in hydroponic with 0.50 mL, reinforcing the findings that hydroponics with minimal seaweed extract results in suboptimal leaf development. The highest growth performance, observed in the aeroponic with 0.75 mL, suggests enhanced biostimulant absorption efficiency and optimal plant development (Silva *et al.,* 2022).

Conversely, the poorest growth, observed in the hydroponic with 0.50 mL, highlights the need for increased supplementation in hydroponic due to lower root zone oxygenation (Mangaiyarkarasi *et al.,* 2020). These results emphasize the importance of optimized nutrient management, particularly within aeroponic systems, for improved turmeric acclimatization and field establishment.

Table 2. Root development of acclimatized turmeric

Treatments	Number of roots	Root length, mm
Acclimatization system		
Hydroponic	17.00b	81.39b
Aeroponic	19.67a	95.09a
Varying seaweed extract concentrations		
0.50 ml	15.00b	75.15b
0.75 mL	18.00a	92.25a
1.00 mL	20.33a	97.72a
1.50 mL	19.50a	87.85ab
Interaction		
Hydroponic × 0.50 mL	13.00d	68.40f
Hydroponic × 0.75 mL	16.00c	76.53ef
Hydroponic × 1.00 mL	20.00a	95.73bc
Hydroponic × 1.50 mL	19.00ab	84.90de
Aeroponic × 0.50 mL	17.00bc	81.90e
Aeroponic × 0.75 mL	21.00a	107.97a
Aeroponic × 1.00 mL	20.67a	99.70ab
Aeroponic × 1.50 mL	20.00a	90.80cd
CV%	4.85	3.53

Root development of acclimatized turmeric

Acclimatization system effect on root development

Acclimatization plays a crucial role in the successful transition of *in vitro*-propagated turmeric to *ex vitro* conditions, with root development serving as a key indicator of plant adaptation. Table 2 presents the number of roots and root length of acclimatized turmeric under different acclimatization systems and varying concentrations of seaweed extract. The acclimatization system significantly influenced both the number of roots and root length of *in vitro*-propagated turmeric. Turmeric acclimatized in the aeroponic system exhibited superior root development, producing an average of 19.67 roots and attaining a root length of 95.09 mm. In contrast, the hydroponic system resulted in significantly fewer roots (17.00) and shorter root length (81.39 mm). The superior root growth observed in the aeroponic system can be attributed to its ability to provide high oxygen availability, which is essential for optimal root respiration, nutrient uptake, and enzymatic activity (Pomoni *et al.,* 2023). The significantly higher number of roots and longer root lengths in aeroponics align with previous studies demonstrating that aeroponic cultivation promotes superior root architecture compared to hydroponics, which may suffer from reduced oxygen diffusion in the root zone (Lakhiar *et al.,* 2018; Hosseinzadeh *et al.,* 2017).

Seaweed extract effect on root development

The application of seaweed extract significantly influenced both root number and root length. The highest root number of 20.33 and longest root length of 97.72 mm were observed in plants treated with 1.00 mL of seaweed extract, followed closely by the 1.50 mL treatment, which produced 19.50 roots with a slightly shorter root length of 87.85 mm. These results suggest that seaweed extract at 1.00 mL provides the optimal concentration for stimulating root proliferation and elongation, likely due to the presence of plant growth-promoting substances such as auxins, cytokinins, and gibberellins (Santos *et al.,* 2019; Mughunth *et al.,* 2024; Kilowasid *et al.,* 2022). Interestingly, the lowest root number of 15.00 and shortest root length of 75.15 mm were observed in plants treated with the lowest concentration of seaweed extract of 0.50 mL, indicating that insufficient supplementation of bioactive compounds may have limited root development due to a saturation point where excessive supplementation does not yield further benefits, potentially due to hormonal imbalances or osmotic stress (Latique *et al.,* 2013; Marschner's 2012).

Synergistic effects of acclimatization and seaweed extract on root development

The interaction between acclimatization system and seaweed extract concentration exhibited significant effects on both root number and root length. Among all treatments, turmeric plants grown in aeroponics with 0.75 mL seaweed extract exhibited the highest root number of 21.00 and the longest root length of 107.97 mm, demonstrating a synergistic effect between aeroponic conditions and moderate seaweed extract application. This suggests that the combination of aeroponics and 0.75 mL seaweed extract enhances root development more effectively than other treatments. The superior performance of aeroponics can be attributed to its ability to provide high oxygenation, which facilitates nutrient uptake and promotes overall root health. Meanwhile, hydroponics, while still effective, resulted in comparatively lower root proliferation and shorter root lengths, underscoring the importance of oxygen availability in root formation. Conversely, the poorest root development was observed in the hydroponic system with 0.50 mL seaweed extract, which resulted in the lowest root number of 13.00 and shortest root length of 68.40 mm. This suggests that suboptimal seaweed extract concentrations, in combination with hydroponic systems, may not adequately stimulate root initiation and elongation, highlighting the need for sufficient biostimulant supplementation to maximize acclimatization success. Additionally, plants grown in aeroponics with 1.00 mL and 1.50 mL seaweed extract exhibited consistently high root numbers (20.67 and 20.00, respectively) and relatively long root lengths (99.70 mm and 90.80 mm, respectively), further confirming the beneficial effects of aeroponics combined with sufficient seaweed extract supplementation. The increasing trend in root development with rising seaweed extract concentration, particularly at 1.00 mL, suggests that seaweed-derived biostimulants contain bioactive compounds such as auxins, cytokinins, and gibberellins that enhance root initiation and elongation (Santos *et al.,* 2019; Mughunth *et al.,* 2024; Muhammad *et al.,* 2022). The slight decline in root length at 1.50 mL may indicate a saturation point where excessive supplementation does not yield further benefits, potentially due to hormonal imbalances or osmotic stress (Latique *et al.,* 2013; Marschner's, 2012). On the other hand, in the hydroponic system, the highest root number (20.00) and longest root length (95.73 mm) were recorded in plants treated with 1.00 mL seaweed extract. This demonstrates that within hydroponic conditions, a slightly higher seaweed extract concentration may be necessary to compensate for lower oxygen availability compared to aeroponics. However, at 1.50 mL concentration, the root length in hydroponics (84.90 mm) decreased slightly, suggesting that excessive seaweed extract may not further enhance root elongation and could even have inhibitory effects.

Biomass accumulation of acclimatized turmeric

Acclimatization system effect on biomass production

The acclimatization of *in vitro*-propagated turmeric was evaluated based on the biomass accumulation in terms of fresh and dry weight (Table 3). The aeroponic system exhibited superior performance in enhancing turmeric biomass compared to the hydroponic system.

Plants acclimatized under aeroponics produced a significantly higher fresh weight of 5.99 grams and dry weight of 1.58 grams than those in the hydroponic system, which recorded lower values of 4.98 grams and 1.20 grams, respectively. The increased biomass under aeroponics may be attributed to the improved aeration and nutrient availability, which are characteristic advantages of this system. In aeroponics, the roots are intermittently misted with nutrient solutions, facilitating higher oxygen uptake and allows roots to access higher levels of oxygen, which is essential for cellular respiration and nutrient uptake, resulting in improved growth performance (Li *et al.,* 2018; Wimmerova *et al.*, 2022). Conversely, in hydroponics, root oxygen availability may be relatively lower due to continuous submersion in nutrient solutions, potentially limiting root function and biomass accumulation.

Table 3. Biomass (grams) of acclimatized turmeric

Treatments	Fresh weight, gm	Dry weight, gm
Acclimatization system		
Hydroponic	4.98b	1.20b
Aeroponic	5.99a	1.58a
Varying seaweed extract concentrations		
0.50 ml	4.58b	1.24b
0.75 mL	5.55ab	1.27ab
1.00 mL	6.14a	1.65a
1.50 mL	5.69ab	1.42ab
Interaction		
Hydroponic × 0.50 mL	4.103e	1.05d
Hydroponic × 0.75 mL	4.303e	1.13cd
Hydroponic × 1.00 mL	6.143ab	1.27bcd
Hydroponic × 1.50 mL	5.396cd	1.36bc
Aeroponic × 0.50 mL	5.056d	1.42b
Aeroponic × 0.75 mL	6.810a	1.41b
Aeroponic × 1.00 mL	6.130ab	2.03a
Aeroponic × 1.50 mL	5.980bc	1.48b
CV%	4.50	5.85

Seaweed extract effect on biomass production

The application of varying concentrations of seaweed extract significantly influenced the biomass accumulation of turmeric. The highest fresh weight of 6.14 grams and dry weight of 1.65 grams were observed at the 1.00 mL concentration, suggesting that this level of supplementation provided the optimal balance of growth-enhancing compounds such as phytohormones, trace minerals, and polysaccharides present in seaweed extract. The positive impact of seaweed extract supplementation on biomass accumulation aligns with previous studies highlighting its role in enhancing plant growth through phytohormones, trace elements, and bioactive compounds (Mughunth *et al.,* 2024; Deolu-Ajayi *et al.,* 2021; Chaturvedi *et al.,* 2022). Furthermore, studies have shown that seaweed extracts contain natural auxins, cytokinins, and gibberellins, which stimulate cell division, root elongation, and biomass production (Yusuf *et al.,* 2021; Comin *et al.,* 2024; Mughunth *et al.,* 2024). The lowest biomass values were recorded at the 0.50 mL concentration, with a fresh weight of 4.58 grams and dry weight of 1.24 grams, indicating that lower concentrations may not supply sufficient bioactive compounds to maximize plant growth. Interestingly, increasing the concentration to 1.50 mL resulted in slightly reduced biomass of 5.69 grams fresh weight and 1.42 grams dry weight, which may indicate a saturation effect where excessive supplementation does not further enhance growth or could disrupt or lead to mild nutrient imbalances (Latique *et al.,* 2013; Marschner's 2012).

Synergistic effects of acclimatization and seaweed extract on biomass production

A highly significant interaction was observed between acclimatization system and seaweed extract concentration, indicating that turmeric's response to seaweed extract varied depending on the system used. The highest fresh weight of 6.81 grams was recorded in the aeroponic system with 0.75 mL seaweed extract, followed closely by aeroponic with 1.00 mL seaweed extract at 6.13 grams. These values suggest that a moderately high concentration of seaweed extract is most effective under aeroponic conditions, likely due to the improved nutrient absorption capacity of aeroponically grown plants. This is supported by previous studies demonstrating that aeroponics enhances the bioavailability of applied biostimulants, allowing plants to utilize nutrients more effectively (Khater, 2015; Comin *et al.,* 2024). Furthermore, the highest dry weight of 2.03 grams was also observed in aeroponics at 1.00 mL seaweed extract, further supporting the superior efficiency of this system in promoting biomass accumulation. In contrast, the lowest fresh and dry weight values were recorded under hydroponics with 0.50 mL seaweed extract, at 4.103 grams and 1.05 grams, respectively. This indicates that lower seaweed extract concentrations are insufficient to maximize growth, particularly in hydroponics, where root absorption dynamics differ from aeroponics. Notably, hydroponic plants supplemented with 1.00 mL seaweed extract exhibited a considerable increase in fresh weight of 6.14 grams, closely matching the performance of aeroponic plants under the same concentration. This suggests that while hydroponic plants require a higher level of seaweed extract supplementation to achieve biomass values comparable to aeroponics, the effectiveness of seaweed extract is still evident in this system. Meantime, among hydroponically grown plants, those treated with 1.50 mL seaweed extract displayed moderate fresh weight of 5.40 grams and dry weight of 1.36 grams, indicating that while biomass improved with increasing seaweed extract levels, the benefits plateaued beyond the 1.00 mL threshold (Latique *et al.,* 2013; Marschner's, 2012). Similarly, aeroponic plants with 1.50 mL seaweed extract exhibited a slightly lower fresh weight (5.98 grams) and dry weight (1.48 grams) compared to the 1.00 mL treatment, reinforcing the observation that excessive seaweed extract does not necessarily result in further growth enhancement.

Survival rate

The results indicating a 100% survival rate for *in vitro*-propagated turmeric across all acclimatization strategies and nutrient concentrations, showcasing its adaptability to soilless systems under controlled conditions. The 100% survival rate of *in vitro*-propagated turmeric in both soilless systems, regardless of seaweed extract concentration, confirms its effectiveness as acclimatization strategies for *in vitro*-propagated plants. The results align with previous studies demonstrating the suitability of hydroponic and aeroponic systems for acclimatizing tissue-cultured plants. These systems provide consistent nutrient availability, oxygenation, and reduced transplant shock, promoting successful establishment (Hosseinzadeh *et al.,* 2017; Gaikwad *et al.,* 2020; Broćić *et al.,* 2021; Ali *et al.,* 2017).

Furthermore, the findings corroborate studies showing that seaweed extract biostimulants do not negatively affect survival rates and may even enhance physiological responses (Comin *et al.,* 2024; Mughunth *et al.,* 2024). The lack of mortality in this study, using seaweed extract concentrations, supports the safe application range suggested by Yuan *et al.,* 2024).

Conclusion

The study highlights that the acclimatization of *in vitro*-propagated turmeric is significantly enhanced by using aeroponic systems and optimal applications of seaweed extract. The aeroponic method outperformed hydroponics in growth performance, root development, and biomass accumulation due to better oxygen and nutrient absorption. The optimal concentration of seaweed extract was found to be 1.00 mL, with a combination of aeroponic conditions and 0.75 mL of seaweed extract yielding the best results. Importantly, all treatments achieved a 100% survival rate, confirming the effectiveness of both systems for transitioning plants to ex vitro environments.

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