Comparison of Dwarf Water Hyssop (*Bacopa monnieri*) in Emerged and Submerged Systems in Aquariums

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Abstract

Dwarf water hyssop (*Bacopa monnieri*) is a popular choice among aquarium enthusiasts for its ease of care and rapid growth. Despite its popularity, research on its suitability as an aquarium plant is scarce. The objective of this study was to assess the effects of various fertilizer formulas and growth performance in both emerged and submerged culture systems. Dwarf water hyssop was cultured for four weeks in emerged and submerged systems using different NPK fertilizer formulas (18-18-18, 25-5-5, 30-20-10, and 8-24-24), alongside a control group without fertilizer. Remarkably, growth performance (i.e. plant height, number of leaves, number of nodes, and root length) and survival rate did not significantly differ between plants with and without fertilizer application in either culture system. Among the fertilizers tested, treatment 4 (NPK 30-20-10) showed the most promising results for dwarf water hyssop growth in both emerged and submerged culture systems. In the emerged system, these treatments led to a minimum height increase (7.96±1.49 cm), a medium number of new leaves (4.41±1.91 leaves/explant), a moderate number of new nodes (3.08±0.29 nodes/explant), and a substantial root system length (2.67±1.16 cm). Conversely, in the submerged system, a minimum height increase (1.65±0.32 cm), medium number of new leaves (1.33±1.66 leaves/explant), moderate number of new nodes (1.08±0.76 nodes/explant), and root system length (0.36±0.86 cm) were observed. Overall, plant morphology and growth performance were superior in the emerged system compared to the submerged system after four weeks of culture. Outstandingly, all plants survived, regardless of fertilizer application of formula, in both culture systems. Given its slow growth, dwarf water hyssop is ideal for aquarists seeking a dwarf aquatic decoration. The emerged culture system is recommended for mass production of this ornamental plant, while the submerged culture system is suitable for elaborate ornamental aquariums.

Keywords: aquatic plant, aquaculture, NPK fertilizer formulas, growth performance, survival rate

Introduction

Water hyssop (*Bacopa monnieri*) is an aquatic plant that is very popular among aquarium hobbyists. The Water hyssop has been widely reported to have medicinal qualities, giving it great commercial value. Given this, biotechnology has been applied to the growing of water hyssop to ensure a plentiful supply for its multiple uses as a medicinal product and as an ornamental plan. It is a glycophytic found in brackish water and is also used to treat many ailments (Jathina & Abdussalam, 2019). It is a medicinal herb found throughout the Indian subcontinent in wet marshy areas (Subashri & Koilpillai, 2014) and it has been used as a traditional medicine to treat anxiety and neurosis (Sanputawong et al., 2018). Water hyssop is known as Brahmi (Sanskrit) in the Indian system of medicine. Due to its high demand as a medicinal herb, it has a high value (Banerjee & Sharivastava, 2008). In Vietnam, water hyssop has not only been used as a traditional medicine to improve intelligence and memory but also as a vegetable (Le et al., 2015). Water hyssop proliferates quickly in wetlands (Sinha et al., 1996). It is a very popular aquarium plant in Turkey because of its characteristics and adaptability under moderately brackish conditions (Karatas & Aasim, 2014). Water hyssop was listed as a threatened species by the International Union for Conversation of Nature (IUCN) because of the high demand, and the small number of species in nature (Subashri & Koilpillai, 2014). Water hyssop has been known by aquarists and is widespread as an ornamental plant (Laohavisuti et al., 2018). It is one of the most uncomplicated, easy-to-grow, fast-growing plants in aquariums that are clean, and have clear water and sufficient nutrition. It can stand strong and upright, touching the surface of the water. However, its rapid growth rate may pose a challenge for some aquarists who wish to use it as aquarium decoration. There has been no research mentioning dwarf water hyssop as an aquarium plant. These dwarf plants may be the most interesting plants for aquarists when designing their small home aquarium.

Owing to the plant being acclimated to living in water directly, it is now possible for aquarists to propagate it commercially (Karatas et al., 2013). Therefore, the production of dwarf water hyssop as an ornamental plant in aquatic conditions should be researched in different aquarium culture systems with various fertilizer formulas to demonstrate the morphology of dwarf water hyssop plant growth. Thus, the objective of this study was to assess the impact of various fertilizer formulas and compare growth performance in both emerged and submerged culture systems for aquarium plants.

Methods and Materials

Plant materials:

Sixty experimental plantlets were sourced from *in vitro* dwarf plants treated with 2.5 mg/L Paclobutrazol (PBZ) (Tauk et al., 2021). Selection criteria included healthy shoots, robust roots and color, and uniformity in size and length. After careful removal from the parent plants, the plantlets underwent rinsing with tap water to eliminate agar adhering to the roots. Subsequently, they were soaked in Betadine antiseptic solution for approximately 2 minutes to safeguard against fungal, bacterial, or viral infections.

Aquarium materials:

An aquariums of size 15x15x25 cm were utilized. Before commencing the experiment, all aquariums were meticulously cleaned with tap water and allowed to dry thoroughly.

Experimental set-up:

In both the emerged and submerged culture systems, the aquariums were prepared with 0.5 cm of gravel rinsed with treated tap water and layered to a thickness of three cm at the bottom. The emerged system aquariums were filled with 0.8 liters of treated tap water, while the submerged system aquariums were filled with two liters. In each aquarium, the respective NPK fertilizer formula was dissolved in the treated water before addition.

Fertilizer application:

The experiments consisted of five treatments, each with three replications, each with four plantlets. The main factors included four NPK fertilizer formulae (treatment 2: 18-18-18, treatment 3: 25-5-5, treatment 4: 30-20-10, and treatment 5: 8-24-24) at a concentration of 10 mg/L, with a non-fertilization treatment (treatment 1) as a control. Four plantlets were introduced into each aquarium on the initial day of the research and cultured under natural lighting conditions.

Throughout the four-week experimental period, fertilizer was added every seven days according to the designated concentration (10 mg/L). Additionally, treated water was intermittently added to maintain the initial water level across all aquariums.

Data collection:

Plant growth parameters: Plant growth parameters were observed and recorded at the onset and conclusion of the study. These parameters included plant height, root length, number of leaves, and number of nodes.

Water quality analysis: Water quality was assessed initially and then weekly over the 4-week duration of the study. Four key water quality parameters were monitored i.e. temperature, pH, dissolved oxygen, and electrical conductivity. All results of water quality analyses were meticulously recorded.

Light intensity: Light intensity measurements were taken at the onset and subsequently weekly using an illuminometer.

Statistical analysis:

All experiments were carried out using a completely randomized design (CRD). The collected data underwent analysis through a Two-way analysis of variance (Two-Way ANOVA). Statistical significances among means of each treatment were determined using Duncan's multiple range test (DMRT) at a confidence level of 99%. The analysis was conducted using the Rstudio program version 1.2.5019.

Results

1. Effects of different fertilizers on survival rate and growth performance of dwarf water hyssop in the emerged and submerged culture systems

1.1 Growth performance

In the emerged culture system, after four weeks of dwarf water hyssop cultivation, all treatments exhibited an increase in plant height, with no significant differences observed at the 0.01 level. However, treatment 3 (NPK 25-5-5) showed the maximum increase in height, with an average increase of 9.34±1.97 cm, while treatment 4 (NPK 30-20-10) had the minimum increase, with an average increase of 7.96±1.49 cm. Although the number of leaves of the dwarf water hyssop increased in all treatments, the differences were not statistically significant ($p>0.01$). Treatment 5 (8-24-24) had the maximum number of leaves, with an average of 5.58±0.14 leaves/explant, while treatment 2 (NPK 18-18-18) had the minimum number of leaves, with 3.50±2.54 leaves/explant. Similarly, the number of nodes of dwarf water hyssop increased in all treatments, but without significant differences ($P>0.01$). The control group exhibited the maximum number of new nodes, with 3.92±0.58 nodes/explant, while treatment 5 (NPK 8-24-24) showed the minimum number of new nodes, with 2.83±0.88 nodes/explant. The roots were elongated in all treatments, but the differences in root length were not statistically significant ($P > 0.01$). Treatment 4 (NPK 30-20-10) had the maximum increase in root length, with an average of 2.67±1.16 cm, while treatment 3 (NPK 25-5-5) had the minimum increase in root length, with an average root length of 2.01±0.47 cm (Table 1).

In the submerged culture system, the cultivation of dwarf water hyssop for four weeks resulted in increased plant height across all treatments. However, these differences were not statistically significant ($p>0.01$). Treatment 5 (NPK 8-24-24) demonstrated the maximum height increase, with an average of 2.35±0.63 cm, while treatment 4 (NPK 30-20-10) showed the minimum increase, with an average of 1.65±0.32 cm. Leaf count also rose in all treatments, though without significant differences ($p>0.01$). Notably, the control group (no fertilizer) displayed the maximum increase in new leaves, with an average of 2.92±0.95 leaves/explant, while treatment 4 (NPK 30-20-10) showed the minimum increase, with an average of

1.33±1.66 leaves/explant. Similarly, the number of nodes increased in all treatments without statistical significance ($p>0.01$). Treatment 3 (NPK 25-5-5) exhibited the maximum increase in new nodes, with an average of 1.75±0.00 nodes/explant, whereas treatment 4 (NPK 30-20-10) showed the minimum increase, with an average of 1.08±0.76 nodes/explant. Root length also increased across all treatments over the experimental period, the differences were not significant ($p>0.01$). Treatment 3 (NPK 25-5-5) demonstrated the maximum increase in root length, with an average of 1.46±0.66 cm, while treatment 5 (NPK 8-24-24) displayed the minimum increase at 0.35±0.42 cm (Table 1).

Additionally, the statistical analysis revealed a significant difference ($p<0.01$) between the emerged culture system and the submerged culture system. However, there was no any differences observed between the four fertilizer formulas (18-18-18, 25-5-5, 30-20-10, and 8-24-24) and the two culture systems (emerged and submerged culture system).

Table 1 Effect of fertilizer application on growth performance of dwarf water hyssop in the emerged and submerged culture systems for 4 weeks (Mean±SD)

Fertilizer (N-P-K)	**Height (cm)**		Average of Fert.	**No. of Leaves**		Average of Fert.	**No. of Nodes**		Average of Fert.	**Root length (cm)**		Average of Fert.
	Emerg.	**Submerg.**		**Emerg.**	**Submerg.**		**Emerg.**	**Submerg.**		**Emerg.**	**Submerg.**	
Control	8.96± 0.65	1.73± 0.08	5.35± 3.98	5.08± 2.18	2.92± 0.95	4.00± 1.92	3.92± 0.58	1.50± 0.50	2.71± 1.41	2.37± 0.54	0.51± 0.57	1.44± 1.13
18-18-18	8.62± 0.80	1.74± 0.27	5.19± 3.81	3.50± 2.54	2.08± 1.38	2.79± 1.98	3.42± 0.52	1.33± 0.72	2.38± 1.27	2.11± 0.75	1.29± 0.86	1.70± 0.85
25-5-5	9.34± 1.09	2.18± 0.48	5.76± 3.99	5.08± 1.38	2.67± 0.38	3.88± 1.60	3.50± 0.66	1.75± 0.00	2.63± 1.05	2.01± 0.47	1.46± 0.66	1.73± 0.59
30-20-10	7.96± 1.49	1.65± 0.32	4.81± 3.59	4.41± 1.91	1.33± 1.66	2.88± 2.33	3.08± 0.29	1.08± 0.76	2.08± 1.21	2.67± 1.16	0.36± 0.86	1.52± 1.56
8-24-24	8.02± 1.24	2.35± 0.63	5.19± 3.23	5.58± 0.14	1.72± 1.49	3.65± 2.32	2.83± 0.88	1.19± 0.39	2.01± 1.08	2.61± 1.36	0.35± 0.42	1.48± 1.53
Average of culture	8.58± 1.07a	1.93± 0.45b		4.73± 1.72a	2.14± 1.22b		3.35±0.65a	1.37± 0.52b		2.36±0.83a	0.79± 0.77b	
Culture system (C)		**			**			**			**	
Fertilizer (F)		ns			ns			ns			ns	
C*F		ns			ns			ns			ns	
C.V. (%)		15.7			45.71			24.71			51.89	

ns = not significant

** = significant at P ≤ 0.01

Means within the same row in each parameter followed by different letters are significantly different using DMRT.

1.2 Survival rate

In both the emerged and submerged culture systems, all treatments, including those with fertilizer formulae and a control (no fertilizer), exhibited a 100% survival rate after four weeks of culture (Table 2).

Table 2 Survival rate of dwarf water hyssop in the emerged and submerged culture systems for 4 weeks (Mean±SD)

Fertilizer formulas	Final survival rate (%)	
	Emerged	Submerged
T_1: Control	100.00±0.00	100.00±0.00
T_2: 18-18-18	100.00±0.00	100.00±0.00
T_3: 25-5-5	100.00±0.00	100.00±0.00
T_4: 30-20-10	100.00±0.00	100.00±0.00
T_5: 8-24-24	100.00±0.00	100.00±0.00
F-test	ns	ns
C.V. (%)	0.00	0.00

ns = not significantly different

2. Environmental condition of dwarf water hyssop in the emerged and submerged culture systems

2.1 Water quality

The water quality of the dwarf water hyssop in the emerged and submerged culture systems with four fertilizer formulas, and a control (no fertilizer), for four weeks, is shown in Table 3. In the emerged system, the water quality parameters were monitored for 4 weeks for dwarf water hyssop cultivation for all plant samples. Electricity conductivity (EC) ranged from 19.77 to 64.30 µS/cm exhibiting an increase by the study's end (Fig. 1A). Water temperature remained consistently between 30.00 and 30.36 °C (Fig.1B), while pH levels ranged from 7.15 to 8.66 (Fig. 1C). Dissolved oxygen (DO) concentrations varied from 3.72 to 8.43 mg/L (Figure 1D), with a decrease noted towards the research's conclusion. Similarly, in the submerged culture system, where the dwarf water hyssop was studied under identical conditions for four weeks, EC levels ranged from 50.36 to 78.33 µS/cm, showing an increasing trend throughout the experiment (Fig.2A). The water temperature maintained a range of 29.33 to 31.33 °C (Fig. 2B), while pH values fluctuated between 7.09 to 8.73 (Fig. 2C). DO concentrations ranged from 3.99 to 8.05 mg/L (Fig. 2D). These findings underscore the importance of consistent monitoring and maintenance of water quality parameters for successful cultivation of dwarf water hyssop in both emerged and submerged culture systems.

Table 3 Water quality of dwarf water hyssop in the emerged and submerged culture systems for 4 weeks

Fert. (N-P-K)	EC (µS/cm)		Temperature (°C)		pH		DO (mg/L)	
	Emerg.	Submerg.	Emerg.	Submerg.	Emerg.	Submerg.	Emerg.	Submerg.
T_1: Control	19.77 - 55.63	50.53 - 78.33	30.00 - 30.36	29.33 - 31.00	7.15 - 8.06	7.09 - 8.73	4.12 - 5.83	3.99 - 5.70
T_2: 18-18-18	20.57 - 60.90	50.73 - 75.36	30.00 - 30.36	29.50 - 31.00	7.29 - 8.66	7.12 - 8.72	4.00 - 5.69	4.83 - 6.02
T_3: 25-5-5	20.30 - 60.43	50.96 - 74.26	30.00 - 30.35	29.33 - 31.00	7.27 - 8.57	7.11 - 8.69	3.92 - 5.45	4.60 - 5.46
T_4: 30-20-10	19.90 - 59.10	50.36 - 74.43	30.00 - 30.36	29.33 - 31.33	7.32 - 8.64	7.14 - 8.69	3.78 - 5.56	4.53 - 6.58
T_5: 8-24-24	20.67 - 64.30	50.90 - 75.66	30.00 - 30.36	29.66 - 31.33	7.20 - 8.43	7.11 - 8.68	3.72 - 8.43	4.84 - 8.05

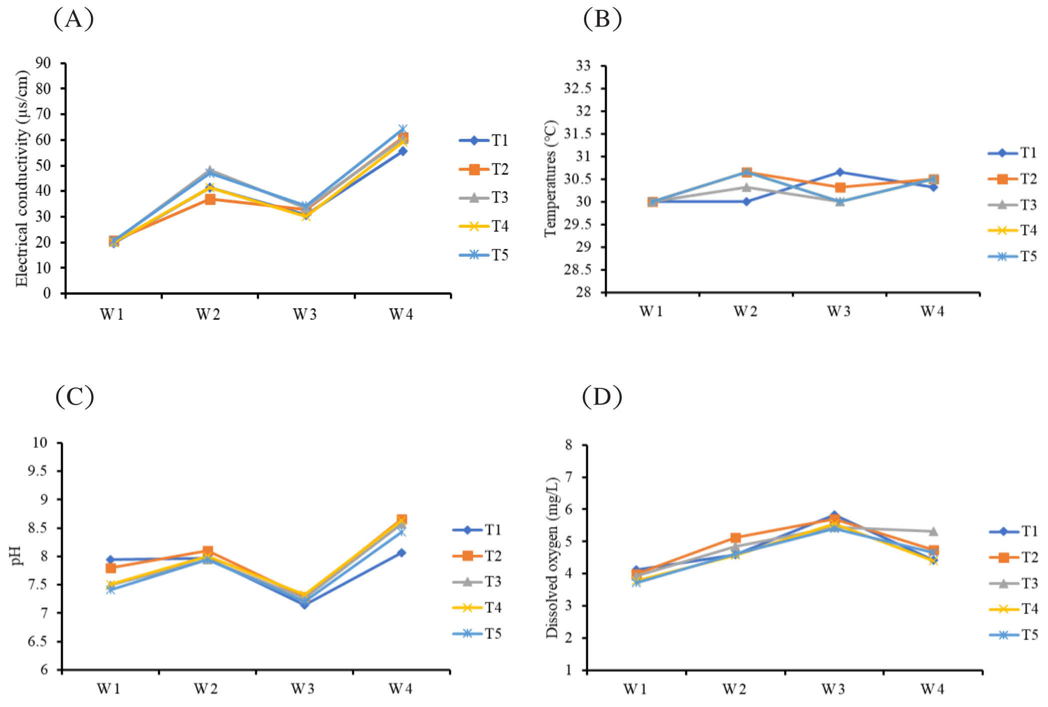


Figure 1 Water quality of dwarf water hyssop in the emerged culture system after 4 weeks. Electrical conductivity (A), Temperature (B), pH (C), Dissolved oxygen (D)

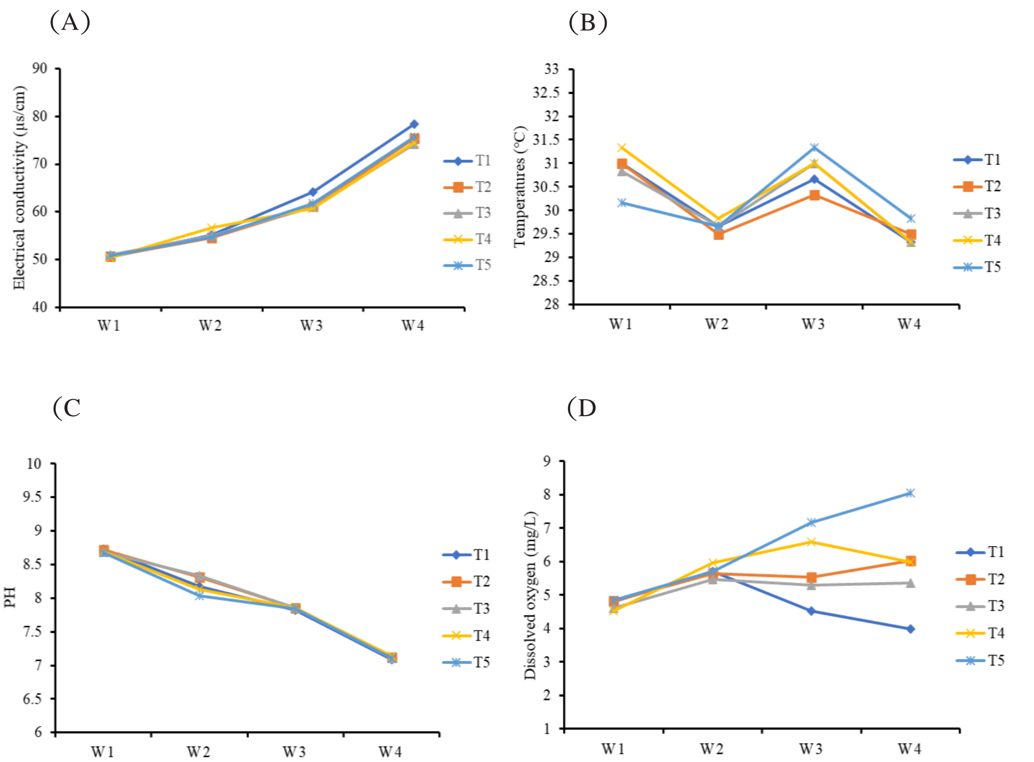


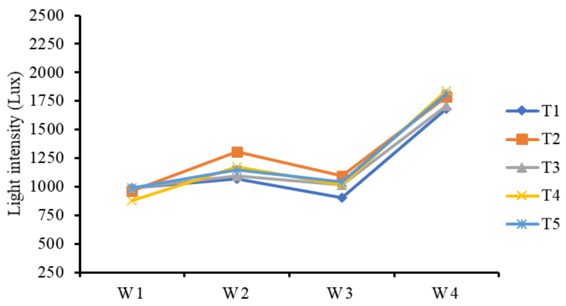
Figure 2 Water quality in the aquariums in the submerged culture system after 4 weeks. Electrical conductivity (A), Temperature (B), pH (C), Dissolved oxygen (D)

2.2 Light intensity

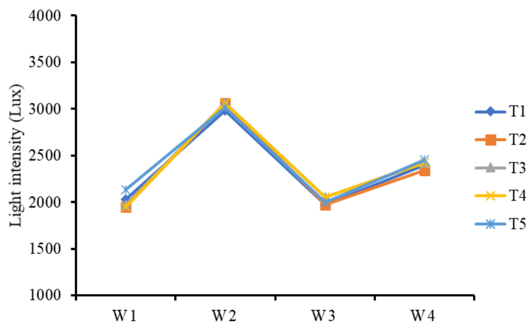
After cultivation of dwarf water hyssop in both the emerged and submerged culture systems under natural light for four weeks, the minimum light intensity observed in the emerged culture experiment was 986.66 lux, with the maximum reaching 1840 lux. Similarly, in the submerged culture experiment, the minimum light intensity recorded was 1846.66 lux, while the maximum was 1946.66 lux, while the maximum was 3066.66 lux (Table 4; Fig. 3.)

Table 4 Light intensity of dwarf water hyssop in the emerged and submerged culture systems for 4 weeks.

Fertilizer formulas (N-P-K)	Light intensity (Lux)			
	Emerged		Submerged	
	Minimum	Maximum	Minimum	Maximum
T_1: Control	906.66	1680.00	1973.33	2986.66
T_2: 18-18-18	960.00	1786.66	1946.66	3066.66
T_3: 25-5-5	986.66	1706.66	1973.33	3066.66
T_4: 30-20-10	880.00	1840.00	1946.66	3066.66
T_5: 8-24-24	986.66	1813.33	2000.00	3013.33



(A)



(B)

Figure 3 Light intensity of dwarf water hyssop in the culture systems for 4 weeks. (A), emerged culture system (B), submerged culture systems

Discussion

1. Effects of different fertilizer formulas on survival rate and growth performance of dwarf water hyssop in the emerged and submerged culture systems

1.1 Growth performance

The findings of this study were aligned with previous research, notably the work of Khalid & Shedeed (2015), who highlighted the pivotal role of nitrogen in synthesizing plant components through various enzymatic activities. The availability of nitrogen in plant cultivation is crucial, particularly during the partitioning of biomass into roots and shoots. Razaq et al. (2017) emphasized the dependency of plant morphology, photosynthesis, and nutrient availability on the nitrogen acquired by the plant. Marschner (2012) further emphasized the importance of providing plants with the appropriate nutrition, including nitrogen, to facilitate efficient growth, flowering, and reproduction. In this experiment, we observed that treatment 4 (NPK 30-20-10), which received a higher nitrogen ratio compared to other treatments, potentially overloading the dwarf water hyssop with nitrogen. This resulted in shorter plants compared to those in other treatments. Dwarf water hyssop is favored as an aquarium plant due to its slow growth and compact size, which are ideal for aquarium settings and contribute to its aesthetic appeal.

In the submerged culture system, all dwarf water hyssop plantlets exhibited upward growth through the water column, alongside other aquatic greenery. This highlights their ornamental value in aquariums. Given the preference for ornamental plants in aquariums for their aesthetic appeal, dwarf plants are particularly sought after due to their slow growth and relatively short stature. Treatment 4 (NPK 30-20-10), which experienced the slowest growth and had the shortest final height by the end of our research, underscores the significance of nitrogen availability in influencing growth dynamics. This observation suggests that nitrogen availability plays a crucial role in determining the growth trajectory of dwarf water hyssop. Overall, our study contributes to understanding the relationship between nitrogen availability and the growth performance of dwarf water hyssop in different culture systems. These insights can inform the development of effective nutrient management strategies to optimize the growth of dwarf water hyssop, particularly in aquarium environments.

Furthermore, the maximum number of leaves can serve as a key indicator of health in dwarf aquatic plants, reflecting their potential for leaf growth during the metabolic process. Leaves play a crucial role as the primary photosynthetic organ for nutrient metabolism. Over evolutionary time, the morphology and anatomy of leaves have adapted to optimize light and CO_2 uptake (Crang et al., 2018). Moreover, leaves require a high ratio of nitrogen (N) for morphological development. However, in our emerged culture system, treatment 5 (NPK 8-24-24), characterized by the lowest N in the ratio, exhibited the maximum number of new leaves per explant. This unexpected finding suggests that factors beyond nitrogen levels may influence leaf growth in dwarf aquatic plants. Additionally, it's worth noting that some leaves from all treatments fell off their shoot stems due to decay caused by initial damage or tearing. Consequently, there was a reduction in new leaves compared to the initial count at the onset of the research. As emphasized by Marschner (2012), leaves are indispensable for aquatic plants to carry out photosynthesis effectively. They rely on sufficient nutrients, particularly nitrogen, to produce healthy and attractive foliage. Insufficient nitrogen can lead to yellowing of leaves and sluggish growth. In our study, control in the submerged culture system demonstrated the maximum number of new leaves per explant. Conversely, treatment 4 (NPK 30-20-10) exhibited the minimum number of new leaves per explant. These results suggest that even with a higher nitrogen ratio, there may be limitations in the production of reproductive organs. Therefore, factors beyond nitrogen availability may also influence leaf growth and overall plant health in dwarf aquatic species. Further research is warranted to elucidate the complex interactions between nutrient ratios, leaf development, and reproductive organ formation in aquatic plants.

For each nodal segment, there were two leaves on the dwarf water hyssop plantlets. The increasing number of nodes across all treatments suggests that the compact leaves facilitated vigorous stem growth (Lawson et al., 2021). Interestingly, despite being cultured with various fertilizer formulas, the number of nodes did not significantly differ from the control group, which received no fertilizer. It is noteworthy that buds, leaves, branches, and twigs originated from the nodal points of the plant. The observed increase in the number of nodes indicates that dwarf water hyssop adapted well morphologically to the submerged culture system in the aquarium environment. Although some initial leaves fell off their stems, all leaves across treatments maintained a healthy green color, devoid of any holes or brown spots. Furthermore, the stems displayed numerous new nodes, indicating continued growth and development.

Root systems play a vital role in plant physiology, absorbing essential elements such as oxygen, water, and macronutrients from the soil and transporting them to the stems, leaves, and flowers. Furthermore, roots store energy produced during photosynthesis, which is crucial for overall plant growth and development (Crang et al., 2018). While plants require sufficient macronutrients, especially nitrogen, phosphorus (P) also holds significance in energy transfer and forms a crucial component of various chemical compounds. Adequate phosphorus levels promote healthy root development and facilitate flower formation (Hiscock, 2023). Insufficient nitrogen uptake by roots, as noted by Marschner (2012), can detrimentally impact plant productivity and their ability to withstand challenging environmental conditions. In our study, phosphorus deficiency led to reduced shoot and root growth. Despite being cultured in the emerged system, which featured gravel at the bottom of the aquariums, both some younger and older roots decayed. Roots are essential for maintaining stem height equilibrium and facilitating nutritional absorption. According to Fan et al. (2017), the depth of plant rooting has a modest effect on environmental stress and ecosystem resilience. Additionally, the length of plant roots serves to mitigate competition within the ecosystem. Moreover, Grossnickle (2005) highlights the critical role of root length in the recognition and establishment of newly planted seedlings. When roots cannot access sufficient water for hydration and sustenance, they become stressed. In our study, despite being planted in gravel, some roots experienced partial decay due to inadequate water availability.

1.2 Survival rate

The dwarf water hyssop from *in vitro* cultures acclimated well in aquatic conditions after four weeks. Dwarf water hyssop plantlets grew vigorously, with green unique foliage, in the emerged and submerged culture system aquarium. The plantlets were able to adapt themselves to the environment in the aquariums even though the roots were stuck in the bottom sediment and grew upward towards the surface of the water. Dwarf water hyssop has plenty of green leaves and is very attractive in the lower levels of the water. The results of this study were consistent with Saha et al. (2020), who mentioned that, when using explants from tissue culture-raised plants, direct shoot regeneration led to the production of more than 100 rooted plants/explant within 8-12 weeks with 85-100% survival in the field after acclimatization, can be expected following optimized protocols. Besides, from comparisons of three different culture systems on growth and bacoside production of *B. monnieri* plantlets studied by Kunakhonnuruk et al. (2023), the plantlets responded differently to different culture systems and survival rate was 100% with no abnormalities detected in all culture systems.

2. Environmental condition of dwarf water hyssop in the emerged and submerged culture systems

2.1 Water quality

The water quality in the aquariums in both culture systems, with four fertilizer formulas, had an electrical conductivity (EC) ranging from 50.36 to 78.33 µS/cm. The continuous increase in EC after dissolving in different fertilizer formulas until the end of the research was similar to the uptake of NPK nutrient solutions on the growth and yields of leaf lettuce (*Lactuca sativa* L.) in stationary culture, showing a simultaneous increase until the end of the research period (Samarakoon et al., 2006). Whereas, the water temperature ranging from 29.33 to 31.33 ºC differed from Aquatic Mag (2019), which reported that water hyssop can grow in water around 24 to 25 ºC and tolerates temperatures from 22 to 28ºC, while Hiscock (2003) indicated that water hyssop tolerates temperatures from 22 to 30ºC. Despite this deviation, the pH value observed during the study remained conducive to plant growth in the emerged culture system. Karatas et al. (2013) recommended an optimal water pH of 8.0 for water hyssop, noting the plant's ability to adapt positively to pH levels ranging from 4.0 to 10. Although the water pH gradually decreased over the research duration, it stayed within suitable ranges as proposed by Karatas et al. (2013). Dissolved oxygen (DO) levels decreased towards the study's conclusion, aligning with conditions favorable for the emerged culture system. The DO range for most freshwater aquatic plants, including *B. monnieri*, falls between 5 and 10 mg/L. However, survival is possible in water with lower DO concentrations, down to approximately 2 mg/L, though growth and metabolic rates may diminish under such conditions (Sandoval, 2018). Dissolved oxygen levels observed in the study were also suitable for the submerged culture system. Hence, this study underscores the role of water quality in facilitating the growth and development of dwarf water hyssop in both the emerged and submerged culture systems over 4 weeks.

2.2 Light intensity

Maintaining a light duration of 10-14 hours daily in aquariums is critical for cultivating aquarium plants, serving as their primary light source for photosynthesis. Water hyssop particularly thrives under bright light conditions, fostering dense growth. Insufficient light can lead to elongated stems, wide spaces between leaves, and an unattractive plant appearance (Hiscock, 2023). Despite relying solely on natural daylight, the light intensity during this research remained adequate, though fluctuating depending on weather conditions, resulting in plants with fleshy leaves and vibrant colors after growing in the emerged aquarium. Tropica (2019) suggest that water hyssop can tolerate low levels of CO_2 and endure high-intensity light. However, inadequate light intensity may cause the lower parts of the plant to rot. Plantlet growth heavily depends on light intensity, crucial for photosynthesis and energy production. Insufficient light can hinder photosynthesis and compromise plant health (Hiscock, 2023). Therefore, optimal plant growth requires high-intensity light for effective photosynthesis. While there's limited reporting on the light intensity requirements for water hyssop in the submerged culture system, the observed range of light intensity during these experiments seems optimal, supporting plant health. However, it's important to note that dwarf water hyssop may encounter growth challenges in low-intensity light conditions within the submerged culture system.

Conclusion and Suggestions

Based on the study findings, it can be concluded that dwarf water hyssop serves as an ideal decorative addition to aquariums owing to its slow growth, particularly evident in its minimal increase in plant height. Furthermore, it appeals to enthusiasts who desire lasting aesthetic charm appeal in their aquatic setting. Notably, the growth performance and survival rate of dwarf water hyssop remained consistent regardless of fertilizer application. They exhibited resilience in environments with minimal fertilizer, such as those containing slight food residues or fish feces, as well as in settings without any added fertilizer. Consequently, aquarists can seamlessly incorporate dwarf water hyssop into their home aquariums and effortlessly regulate plant height at a minimal cost.

In summary, the emerged culture system exhibited superior plant morphology and growth performance compared to the submerged culture system after four weeks of cultivation. Remarkably, all plants thrived irrespective of fertilizer application or formula, across both culture systems. With its slow growth, dwarf water hyssop emerges as an ideal choice for aquarists in search of diminutive aquatic decorations. For mass production of this ornamental plant, the emerged culture system is recommended, whereas the submerged culture system is better suited for elaborate ornamental aquarium setups.

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Author Contributions

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Conflict of Interests

All authors declare that they have no conflicts of interest.

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References

Aquatic Mag. (2019). *Bacopa monnieri* caresheet. https://aquaticmag.com/aquarium-plants/bacopa-monnieri-caresheet/

Banerjee, M., & Sharivastava, S. (2008). An improved protocol for *in vitro* multiplication of *Bacopa monnieri* (L.). *World Journal of Microbiology and Biotechnology*, *24*, 1355-1359. https://doi.org/10.1007/s11274-007-9612-3

Carr, G. M., Duthie, H. C., & Taylor, W. D. (1997). Models of aquatic plant productivity: A review of the factors that influence growth. *Aquatic Botany*, *59*, 195-215. https://doi.org/10.1016/S0304-3770(97)00071-5

Crang, R., Lyons-Sobaski, S., & Wise, R. (2018). *Plant anatomy: A concept-based approach to the structure of seed plants.* Springer Cham. https://doi.org/10.1007/978-3-319-77315-5

Fan, Y., Macho, G. M., Jobbágy, E. G., Jackson, R. B., & Casal, C. O. (2017). Hydrologic regulation of plant rooting depth. *Proceedings of National Academy of Sciences*, *114*(40), 10572-10577. https://doi.org/10.1073/pnas.1712381114

Grossnickle, S. C. (2005). Importance of root growth in overcoming plant stress. *New Forests*, *30*, 273-294. https://doi.org/10.1007/s11056-004-8303-2

Hiscock, P. (2003). *Encyclopedia of aquarium plants.* Barron's Educational Series.

Jathina, M., & Abdussalam, A. K. (2019). Histological and morphological response of *Bacopa monnieri* (L.) Pennell in glycophytic and halophytic condition. *International Journal of Pharmaceutical Science and Research*, *10*(1), 407-411. https://doi.org/10.13040/IJPSR.0975-8232.10(1).407-11

Karatas, M., & Aasim, M. (2014). Efficient in vitro regeneration of medicinal aquatic plant water hyssop (*Bacopa monnieri* L. Pennell). *Pakistan Journal of Agricultural Sciences*, *51*(3), 667-672. http://www.pakjas.com.pk

Karatas, M., Aasim, M., Dogan, M., & Khawar, K. M. (2013). Adventitious shoot regeneration of the medicinal aquatic plant water hyssop (*Bacopa monnieri* L. Pennell) using different internodes. *Archives of Biological Sciences*, *65*(1), 297-303. https://doi.org/10.2298/ABS1301297K

Khalid, K. A., & Shedeed, M. R. (2015). Effect of NPK and foliar nutrition on growth, yield and chemical constituent in *Nigella sativa* L. *Journal of Materials and Environmental Science*, *6*(6), 1709-1714. http://www.researchgate.net

Kunakhonnuruk, B., Inthima, P., & Kongbangkerd, A. (2023). Improving bacoside yield of *Bacopa monnieri* (L.) Wettst. in temporary immersion system by increasing immersion time and lowering the intervals. *Industrial Crops & Products*, *191*, 115859. https://doi.org/10.1016/j.indcrop.2022.115859

Laohavisuti, N., Ruangdej, U., & Wangwibulkit, S. (2018). Effect of Kinetin and IAA on growth and antioxidants in *Bacopa monnieri*. *King Mongkut's Agricultural Journal*, *35*(2), 76-83. https://li01.tci-thaijo.org/index.php/agritechjournal/article/download/158101/114505/432900

Lawson, J. W., Fennell, M., Smith, M. W., & Bacon, K. L. (2021). Regeneration and growth in crowns and rhizome fragments of Japanese knowtweed (*Reynoutria japonica*) and desiccation as a potential control strategy. *PeerJ*, *9*, e11783. https://doi.org/10.7717/peerj.11783

Le, X. T., Pham, H. T. N., Nguyen, T. V., Nguyen, K. M., Tanaka, K., Fujiwara, H., & Matsumoto, K. (2015). Protective effects of *Bacopa monnieri* on ischemia-induced cognitive deficits in mice: The possible contribution of bacopaside I and underlying mechanism. *Journal of Ethnopharmacology*, *164*, 37-45. https://doi.org/10.1016/j.jep.2015.01.041

Marschner, P. (2012). *Marschner's mineral nutrition of higher plants* (3rd ed.). Elsevier Academic Press. https://doi.org/10.1016/C2009-0-63043-9

Razaq, M., Zhang, P., Shen, H., & Salahuddin. (2017). Influence of nitrogen and phosphorous on the growth and root morphology of Acer mono. *PLoS ONE*, *12*(2), e0171321. https://doi.org/10.1371/journal.pone.0171321

Saha, P. S., Sarkar, S., Jeyasri, R., Muthuramalingam, P., Ramesh, M., & Jha, S. (2020). In Vitro Propagation, Phytochemical and Neuropharmacological Profiles of *Bacopa monnieri* (L.) Wettst.: A Review. *Plants*, *9*(4), 411. https://doi.org/10.3390/plants9040411

Samarakoon, U. C., Weerasinghe, P. A., & Weekrakkody, W. A. P. (2006). Effect of electrical conductivity [EC] of the nutrient solution on nutrient uptake, growth, and yield of leaf lettuce (*Lactuca sativa* L). in stationary culture. *Tropical Agricultural Research, 18*, 13-21. http://www.researchgate.net

Sandoval, J. R. (2018). *Bacopa monnieri (water hyssop)*. https://www.cabidigitallibrary.org/doi/10.1079/cabicompendium.112638

Sanputawong, S., Raknim, T., & Khawniam, T. (2018). Effects of plant growth regulator and activated charcoal on callus formation and plant regeneration of *Bacopa monnieri* (L.). *Songklanakarin Journal of Plant Science, 5*(1), 7-12. http://www.sjplantscience.com

Sinha, S., Gupta, M., & Chandra, P. (1996). Bioaccumulation and biochemical effects of mercury in the plant *Bacopa monnieri* (L.). *Environmental Toxicology and Water Quality, 11*, 105-112. https://doi.org/10.1002/(SICI)1098-2256(1996)11:2<105: AID-TOX5>3.0.CO;2-D

Subashri, B., & Koilpillai, K. Y. (2014). *In vitro* regeneration of *Bacopa monnieri* (L.) Pennel: A multipurpose medicinal plant. *International Journal of Pharmacy and Pharmaceutical Science, 6*(4), 559-563. http://www.researchgate.net

Tauk, C., Chuaduangpui, P., & Khawniam, T. (2021). Effects of explants on plant regeneration and cincentration of paclobutrazol on morphological responses of Dwarf water hyssop (*Bacopa monnieri*). *Narasuan University Journal: Science and Technology, 29*(3), 56-66. https://doi.org/10.14456/nujst.2021.26

Tropica. (2019). *Bacopa 'Compact'*. https://tropica.com/en/plants/plantdetails/Bacopa'Compact'(044A)/4467