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RESEARCH ARTICLE

Effect of nutrient compositions on growth of ornamental foliage plants in vertical gardening

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Abstract

An experiment was conducted to investigate the effect of nutrient compositions on the growth of ornamental foliage plants in vertical gardening. Three species, Philodendron, Syngonium and Pandanus, were grown under different nutrient compositions in a completely randomized design with a factorial concept and three replications. The study took place from November 2022 to March 2024 at the Floricultural Research Station, Agricultural Research Institute, Rajendranagar, Hyderabad. Over the two-year study, the treatment combination N2P2 (N2: 19:19:19 @ 2g/l + Micronutrient spray @ 4g/l with P_2: Syngonium) showed the best results in terms of leaf area (941.08 cm^2), survival percentage (100 %), number of suckers per plant (3.45), dry weight of root (0.737 g) and root length (27.79 cm). Meanwhile, N2P3 (N2: 19:19:19 @ 2g/l + Micronutrient spray @ 4g/l with P3: Pandanus) exhibited the maximum plant spread (N-S: 42.08 cm, E-W: 41.47 cm), number of leaves per plant (22.70), leaf thickness (1.21 mm) and leaf length (26.81 cm) at 180 days after planting (DAP).

Keywords: growth parameters; nutrient composition; ornamental foliage plants; vertical gardening

Introduction

Awareness of environmental issues, particularly pollution, is rapidly increasing, driving the popularity of eco-friendly and functional sustainable gardening practices. In this context, vertical gardening has emerged as a promising solution to urban challenges such as poor air quality, urban heat islands and space limitations, while enhancing aesthetic appeal. As land availability shrinks and high-rise construction expands, vertical gardens have become integral to modern landscaping and green architecture. Although the concept dates to 600 BC with the Hanging Gardens of Babylon, it was not widely adopted by other cultures such as the Persians, Mughals, or Europeans. Renewed interest in vertical gardens has emerged due to rapid urbanization and the need to optimize limited horizontal space for greenery (1).

The idea was further developed by Stanly Hart White, a professor of Landscape Architecture at the University of Illinois, who introduced "Botanical Bricks" modular plant units designed to green vertical surfaces using flowering vines. Vertical gardens, also known as living wall systems or green walls, consist of modular plant systems attached to interior or exterior walls. These systems are gaining popularity in the 21st century, reflecting the broader shift toward green and sustainable building practices. Vertical gardens not only serve as visually striking focal points but also contribute to cooling effects, reducing indoor temperatures by approximately 5 °C compared to outdoor temperatures (2).

The success of vertical gardens depends heavily on proper plant selection, growing media, nutrient management and environmental conditions. Among these, nutrient composition is critical, as it directly affects plant health, growth, vigor and overall performance (1). Optimal levels of macronutrients like nitrogen, phosphorus and potassium promote root and shoot development, while micronutrients such as iron, magnesium and calcium are essential for physiological and metabolic processes. Additionally, vertical systems require media with appropriate pH, electrical conductivity (EC) and drainage properties to support plant health under gravity-fed irrigation systems (2). Despite the rising popularity of vertical gardens, there is limited research focused on foliage ornamental plants, which are ideal for such systems due to their dense foliage, adaptability to semi-shade and year-round aesthetic value. This study investigates the effect of different nutrient compositions on the growth, physiological traits and root development of three ornamental foliage plants *Philodendron erubescens* K.Koch & Augustin 'Gold', *Syngonium podophyllum* Schott and *Pandanus veitchii* under vertical gardening conditions. These species were chosen for their morphological diversity, decorative appeal and adaptability to vertical environments.

This research is one of the few systematic studies evaluating nutrient optimization specifically for ornamental foliage species in vertical gardens. It integrates ornamental horticulture with vertical landscaping by testing three diverse species under structured nutrient regimes, offering valuable recommendations for sustainable and visually impactful green wall designs.

Materials and Methods

The present investigation was carried out at the Floriculture Research Station, Agricultural Research Institute, Rajendranagar, under Sri Konda Laxman Telangana State Horticultural University, Hyderabad, from November 2022 to March 2024. The study was designed to evaluate the effect of different nutrient compositions on the growth and development of ornamental foliage plants in a vertical garden system.

Experimental design and layout

The experiment were laid out in a Factorial Completely Randomized Design (FCRD) with twelve treatment combinations and three replications. The two factors under study were:

Factor I – Ornamental foliage species

P_1: *Philodendron erubescens* K.Koch & Augustin 'Gold' (Blushing Philodendron)

P_2: *Syngonium podophyllum* Schott (Arrowhead Vine)

P_3: *Pandanus veitchii* (Variegated Screw Pine)

Factor II – Nutrient compositions

N_1: 19:19:19 @ 1 g/L (via fertigation) + Micronutrient spray @ 2 /L (foliar)

N_2: 19:19:19 @ 2 g/L (via fertigation) + Micronutrient spray @ 4 g/L (foliar)

N_3: One fertilizer sticks per pot (slow release)

N_4: 19:19:19 @ 1 g/L (via fertigation only) **-**Control treatment

Experimental setup

A metallic iron mesh stand (10 ft x 5 ft) was constructed to support the vertical garden system. A 50 % shade net was installed over the experimental site to create a semi-shaded environment, suitable for the selected ornamental foliage species. Each vertical frame accommodated six treatments and each treatment plot contained 15 individual pots. Each pot measured 5" x 4" (L x W) and was considered an individual experimental unit. Pots were randomly arranged within each frame using a random number method to avoid positional bias and ensure even light and moisture distribution. A drip irrigation system was installed to deliver water based on seasonal needs: once every 2–3 days during summer and once every 4–5 days in winter. Fertigation was administered through the same drip lines, while micronutrients were applied as a foliar spray every 30 days, using a hand-held sprayer.

Data Collection

Observations were recorded at 30, 90 and 180 DAP on various parameters, including: Growth parameters: plant height, number of leaves, leaf area Physiological parameters: chlorophyll content, visual quality Root traits: root length, root mass media parameters: soil pH, EC and moisture content A visual representation of plant performance over time is provided in Fig. 1.

Statistical analysis

The collected data were statistically analyzed using Analysis of Variance (ANOVA) under the Factorial CRD framework (3). The F-test at 5 % level of significance was used to test treatment effects. When significant differences were observed, Critical Difference (CD) values were calculated to compare means. Interaction effects between plant species and nutrient treatments were analyzed and interpreted wherever found significant. All statistical analyses were performed using SPSS.

Results and Discussion

Growth parameters

Plant height (cm)

Pooled data at 180 DAP, the maximum plant height (30.95 cm) which recorded with N_2- 19:19:19 at 2g /l + micronutrient spray at 4g / l, followed by N_1- 19:19:19 at 1g /l + micronutrient spray at 2g / l (27.44 cm) (Table 1). Whereas N_3- one fertilizer stick / pot recorded significantly minimum plant height (21.58 cm). Significant difference was observed among different ornamental foliage plants with

a) At 30 DAP

b) At 60 DAP

c) At 90 DAP

Fig. 1. Overall view of experiment on effect of different nutrient compositions on growth of ornamental foliage plants in Vertical Garden at a) 30, b) 90 and c) 180 DAP.

Table 1. Effect of different nutrient compositions on plant height (cm), plant spread (N-S), plant spread (E-W) at 180 days after planting in vertical garden

Treatments	Plant height (cm)				Plant spread (N-S)				Plant spread (E-W)			
	P_1	P_2	P_3	Mean	P_1	P_2	P_3	Mean	P_1	P_2	P_3	Mean
N_1	30.01	25.17	27.15	27.44	32.13	28.85	40.16	33.71	31.76	29.24	39.25	33.42
N_2	33.71	28.61	30.52	30.95	33.23	31.61	42.08	35.64	33.16	33.08	41.27	35.83
N_3	21.93	21.10	21.70	21.58	24.55	23.44	28.29	25.43	24.44	23.36	27.66	25.15
N_4	27.58	23.13	25.24	25.32	27.67	26.68	35.02	29.79	28.37	27.37	34.93	30.22
Mean	28.31	24.50	26.15		29.39	27.65	36.39		29.43	28.26	35.78	

	Plant height S.Em ±	Plant height CD (5 %)	Plant spread (N-S) S.Em ±	Plant spread (N-S) CD (5 %)	Plant spread (E-W) S.Em ±	Plant spread (E-W) CD (5 %)
Ornamental foliage plants (P)	0.12	0.36	0.20	0.57	0.19	0.56
Nutrient compositions (N)	0.14	0.42	0.23	0.66	0.22	0.65
PXN	0.25	0.73	0.39	1.15	0.39	1.12

Factor I: Ornamental foliage plants (P)- **P1**- Philodendron **P2**- Syngonium **P3**- Pandanus

Factor II: Nutrient compositions (N)-

N1: 19:19:19 @ 1g / l + micronutrient spray @ 2g / l

N2: 19:19:19 @ 2g / l + micronutrient spray @ 4g / l

N3: 1 fertilizer stick / pot

N4: 19:19:19 @1g / l

respect to plant height at 180 DAP. The maximum plant height (28.31 cm) was recorded with P_1- Philodendron followed by P_3- Pandanas (26.15 cm). Minimum plant height (24.50 cm) was observed with P_2- Syngonium. In the interactions, N_2P_1- 19:19:19 at 2g /l + micronutrient spray at 4g / l + P_1-Philodendron recorded significantly maximum plant height (33.71 cm) followed by N_2P_3- 19:19:19 at 2g /l + micronutrient spray at 4g / l + Pandanus (30.52 cm). While N_3P_2- 1 fertilizer stick / pot + Syngonium recorded minimum plant height (21.10 cm).

Plant spread (cm)

Plant spread (N-S): At 180 DAP (2022 - 23 and 2023 – 24) the maximum plant spread (35.64 cm) which recorded with N_2- 19:19:19 at 2g /l + micronutrient spray at 4g / l, followed by N_1- 19:19:19 at 1g /l + micronutrient spray at 2g / l (33.71 cm) (Table 1). Whereas N_3- one fertilizer stick / pot recorded significantly minimum plant spread (25.43 cm). Significant difference among different ornamental foliage plants was reported with respect to plant spread at 180 DAP. The maximum plant spread (36.39 cm) was recorded with P_3- Pandanus followed by P_1-Philodendron (29.39 cm). Minimum plant spread (27.65 cm) was observed with P_2- Syngonium. In the interactions, N_2P_3- 19:19:19 at 2g /l + micronutrient spray at 4g / l + Pandanus recorded significantly maximum plant spread (42.08 cm) followed by N_2P_3- 19:19:19 at 2g /l + micronutrient spray at 4g / l + Pandanus (40.16 cm). While N_3P_2- 1 fertilizer stick / pot + Syngonium recorded minimum plant spread (23.44 cm).

Plant spread (E-W): At 180 DAP (2022 - 23 and 2023 – 24), the maximum plant spread (35.83 cm) which recorded with N_2- 19:19:19 at 2g /l + micronutrient spray at 4g / l, followed by N_1- 19:19:19 at 1g /l + micronutrient spray at 2g / l (33.42 cm) (Table 1). Whereas N_3- one fertilizer stick / pot recorded significantly minimum plant spread (25.15 cm). Significant difference among different ornamental foliage plants was reported with respect to plant spread at 180 DAP. The maximum plant spread (35.78 cm) was recorded with P_3- Pandanus followed by P_1-Philodendron (29.43 cm). Minimum plant spread (28.26 cm) was observed with P_2- Syngonium. In the interactions, N_2P_3- 19:19:19 at 2g /l + micronutrient spray at 4g / l + Pandanus recorded significantly maximum plant spread (41.27 cm) followed by N_2P_3- 19:19:19 at 2g /l + micronutrient spray at 4g / l + Pandanus (39.25 cm). While N_3P_2- 1 fertilizer stick / pot + Syngonium recorded minimum plant spread (23.36 cm).

The study highlights the significant impact of nutrient concentration on plant spread and overall plant growth. One previous report observed that increasing the concentration of essential nutrients, namely nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and Sulphur (S) resulted in a maximum increase in plant height (Table 1) plant spread (Table 1) (4). A larger canopy is particularly beneficial in vertical gardening, as it covers more surface area, effectively masking undesirable portions of building walls. Nitrogen, a key component of nucleic acids, is crucial for plant growth. It contributes to the formation of protoplasm, which is essential for cell enlargement, division and overall plant development (4). Micronutrients play a vital role by activating various enzymes involved in chlorophyll synthesis and other physiological processes. These factors collectively promote cell differentiation, division and multiplication, which contribute to increased photosynthesis and improved translocation of food materials. Consequently, this results in a greater plant height and plant spread. The present study corroborates these findings, demonstrating that the application of a balanced nutrient mix (19:19:19 @ 2g/l) combined with micronutrient spray (4g/l) resulted in optimal growth of ornamental plants. The provision of both macro and micronutrients in adequate concentrations likely facilitated enhanced vegetative parameters and plant spread. These observations are consistent with similar previous studies in gerbera (5), in chrysanthemum (6) and in China aster (7), all of which noted improved plant growth and spread due to optimal nutrient application.

Number of leaves per plant

At 180 DAP (2022 - 23 and 2023 – 24), the maximum number of leaves per plant (17.08) which recorded with N_2- 19:19:19 at 2g /l + micronutrient spray at 4g / l, followed by N_1- 19:19:19 at 1g /l + micronutrient spray at 2g / l (15.32). Whereas N_3- one fertilizer stick / pot recorded significantly minimum number of leaves per plant (11.19) (Table 2). Significant difference among different ornamental foliage plants was recorded with respect to number of leaves per plant at 180 DAP. The maximum number of leaves per plant (19.10) was recorded with P_3- Pandanus followed by P_1-Philodendron (13.93). Minimum number of leaves per plant (10.59) was observed with P_2- Syngonium. In the interactions, N_2P_3- 19:19:19 at 2g /l + micronutrient spray at 4g / l + Pandanus recorded significantly maximum number of leaves per plant (22.70) followed by N_1P_3-

Table 2. Effect of different nutrient compositions on number of leaves per plant, leaf area (cm^2), leaf length (cm) at 180 DAP in vertical garden

Treatments	Number of leaves per plant				Leaf area (cm^2)				Leaf length (cm)			
	P_1	P_2	P_3	Mean	P_1	P_2	P_3	Mean	P_1	P_2	P_3	Mean
N_1	14.91	11.03	20.01	15.32	859.20	816.68	659.73	778.54	14.65	10.80	25.07	16.84
N_2	16.72	11.81	22.70	17.08	1023.38	941.08	781.71	915.39	15.24	11.33	26.81	17.79
N_3	9.80	8.97	14.80	11.19	397.98	540.38	334.10	424.15	13.46	9.41	21.05	14.64
N_4	14.30	10.57	18.91	14.59	703.74	759.35	546.41	669.83	14.64	10.27	22.04	15.65
Mean	13.93	10.59	19.10		746.08	764.37	580.49		14.50	10.45	23.74	
	S.Em ±		CD (5 %)		S.Em ±		CD (5 %)		S.Em ±		CD (5 %)	
Ornamental foliage plants (P)	0.08		0.25		7.95		23.19		0.12		0.36	
Nutrient compositions (N)	0.10		0.28		9.18		26.78		0.14		0.41	
PXN	0.17		0.49		15.89		46.39		0.24		0.71	

Factor I: Ornamental foliage plants (P)- **P1**- Philodendron **P2**- Syngonium **P3**- Pandanus

Factor II: Nutrient compositions (N)-

N1: 19:19:19 @ 1g / l + micronutrient spray @ 2g / l

N2: 19:19:19 @ 2g / l + micronutrient spray @ 4g / l

N3: 1 fertilizer stick / pot

N4: 19:19:19 @1g / l

19:19:19 at 2g /l + micronutrient spray at 2g / l + Pandanus (20.01). While N_3P_2- 1 fertilizer stick / pot + Syngonium recorded minimum number of leaves per plant (8.97).

The results clearly indicate that the balanced application of NPK, combined with foliar micronutrients, significantly enhanced leaf production across all species, with *Pandanus veitchii* producing the highest number of leaves. This outcome is likely attributable to its inherent growth habit and leaf-producing capacity, as Pandanus is naturally a rosette-forming plant with active meristematic regions that favor leaf proliferation.

While nitrogen's role in promoting chlorophyll synthesis and vegetative growth is well established, the differential response among species suggests that nutrient-use efficiency and uptake capacity vary between plant types. Philodendron and Syngonium, though also foliage-rich species, exhibited comparatively fewer leaves, possibly due to their less aggressive growth architecture or slower nutrient uptake under vertical conditions. This aligns with findings from previous study reported that species-specific responses can be as significant as treatment effects (8). Moreover, the enhanced leaf number under treatments with micronutrient sprays points to the synergistic effect of macro and micronutrients, particularly under vertical conditions where root zone nutrient availability might be limited due to constrained soil volume. The observed improvement likely stems not just from textbook nutrient functions, but from the targeted delivery of micronutrients through foliar sprays, which circumvent root competition and quickly influence physiological processes like cell elongation, photosynthesis and assimilate transport (9). Sunder Some findings similarly reported that foliar-applied micronutrients significantly increased vegetative traits in ornamental crops, especially when root uptake was restricted (5, 8).

Interestingly, potassium though not structurally incorporated may have played a key role in stomatal regulation and enzyme activation, indirectly enhancing photosynthetic efficiency and carbohydrate partitioning towards leaf expansion (4). The observed trends reinforce the importance of a balanced and species-specific nutrient approach in vertical gardening systems. These results are consistent with earlier work (10) but also highlight the need to tailor nutrient delivery based on plant morphology and growing system constraints.

Leaf area (cm^2)

At 180 DAP (2022 - 23 and 2023 – 24), the maximum leaf area (915.39 cm^2) which recorded with N_2- 19:19:19 at 2g /l + micronutrient spray at 4g / l, followed by N_1- 19:19:19 at 1g /l + micronutrient spray at 2g / l (778.54 cm^2). Whereas N_3- one fertilizer stick / pot recorded significantly minimum leaf area (424.15 cm^2) (Table 2). Significant difference was recorded on leaf area among different ornamental foliage plants at 180 DAP. The maximum leaf area (764.37 cm^2) was recorded with P_2- Syngonium on par with P_1-Philodendron (746.08 cm^2). Whereas the minimum leaf area (580.49 cm^2) was observed with P_3- Pandanus (Table 2). In the interactions, N_2P_1- 19:19:19 at 2g /l + micronutrient spray at 4g / l + Philodendron recorded significantly maximum leaf area (1023.38 cm^2) followed by N_2P_2- 19:19:19 at 2g /l + micronutrient spray at 4g / l + Syngonium (941.08 cm^2). While N_3P_3- 1 fertilizer stick / pot + Pandanus recorded minimum leaf area (334.10 cm^2).

The findings of the experiment indicate that a balanced application of fertilizer significantly influenced leaf area. However, the leaf area varied among the species, maximum in Syngonium (P_2) and leaf area in Philodendron (P_1) accordingly to their vertical growth habit but completely influenced by balanced nutrition within the species. N plays a crucial role by increasing both the number and size of leaf cells, leading to an overall enlargement of leaf size. Additionally, the application of phosphorus and potassium at required concentration enhanced nutrient uptake, which likely boosted photosynthesis and chlorophyll formation, further contributing to increased leaf area in all the species. These observations are consistent with the results reported by one previous study noted similar effects on leaf area (11). Furthermore, the previous findings align with the current work with similar documentation of increased leaf area and a higher number of leaves in "golden rods" plants with higher nitrogen concentrations (12). Thus, the data supports the notion that balanced fertilization promotes greater leaf area through enhanced cellular and metabolic processes.

Leaf length (cm)

1 At 180 DAP (2022 - 23 and 2023 – 24), the maximum leaf length (17.79 cm) which recorded with N_2- 19:19:19 at 2g /l + micronutrient spray at 4g / l, followed by N_1- 19:19:19 at 1g /l + micronutrient spray at 4g / l (16.84 cm). Whereas N_3- one fertilizer stick / pot recorded significantly minimum leaf length (14.64 cm) (Table 2). Significant difference Among different ornamental foliage plants was reported with respect to leaf thickness at 180 DAP. The maximum leaf length (23.74 cm) was recorded with P_3- Pandanus followed by P_1- Philodendron (14.50 cm). Minimum leaf length (10.45 cm) was observed with P_2- Syngonium. In the interactions, N_2P_3- 19:19:19 at 2g /l + micronutrient spray at 4g / l + Pandanus recorded significantly maximum leaf length (26.81 cm) which was followed by N_1P_3- 19:19:19 at 2g /l + micronutrient spray at 4g / l + Pandanus (25.07 cm). While N_3P_2- 1 fertilizer stick / pot + Syngonium recorded minimum leaf length (9.41 cm).

The application of N_2P_3 (19:19:19 at 2 g/l) combined with micronutrient spray (4 g/l) significantly enhanced leaf length in all the three species. These improvements can be attributed to the increased nitrogen supply in optimum dose of both macro and micronutrients. The optimum availability of nutrients aided in cell enlargement, division and overall increase in leaf characters. The micronutrient application further stimulated metabolic activities by enhancing cell elongation, differentiation and enlargement. These effects boosted photosynthesis and the translocation of food materials, resulting in increased leaf length (13). Similar findings were reported by some prior findings with the observation of improved leaf development in gerbera with optimal nutrient and micronutrient applications (5, 8).

Survival per centage (%)

At 180 DAP (2022 - 23 and 2023 – 24), the maximum survival percentage (94.44 %) which recorded with N_2- 19:19:19 at 2g /l + micronutrient spray at 4g / l, at par with N_1- 19:19:19 at 1g /l + micronutrient spray at 2g / l (93.33 %) and N_4- 19:19:19 at 1g /l (93.33 %). Whereas N_3-one fertilizer stick / pot recorded significantly minimum survival percentage (89.89 %). (Table 3). Significant difference Among different ornamental foliage plants was reported with respect to survival percentage at 180 DAP. The maximum survival percentage (96.67 %) was recorded with P_2- Syngonium at par with P_1-Philodendron (92.92 %). Minimum survival percentage (87.92 %) was observed with P_3- Pandanus. In the interactions, N_2P_2- 19:19:19 at 2g /l + micronutrient spray at 4g / l + Syngonium recorded significantly maximum survival percentage (100.00 %). Whereas N_3P_3- 1 fertilizer stick / pot + Pandanus recorded minimum survival percentage (83.33 %).

The survival of various plant species under indoor conditions can be significantly influenced by the inherent varietal differences among them. Insufficient nutrient and light availability often contribute to plant mortality and reduced survival rates. The treatment N_2(19:19:19 at 2g /l) combined with micronutrient spray (4g /l) provided a comprehensive supply of both macro and micronutrients, which supported healthy plant growth. In contrast, reduced nutrient concentrations failed to meet the minimum requirements necessary for the growth of certain plant species, leading to increased mortality and lower survival percentages in N_3 (one Fertilizer stick / pot).

Number of suckers per plant

At 180 DAP, a significant effect of both nutrient treatments and plant species was observed on sucker production (Table 3). The highest number of suckers per plant (2.56) was recorded with N2 (19:19:19 @ 2 g/L + micronutrient spray @ 4 g/L), followed by N1 (2.39). The lowest was observed in N3 (fertilizer stick/pot), which produced only 1.22 suckers per plant, indicating that slow-release fertilizer alone may not sufficiently meet the dynamic nutrient demands of vertical gardening systems.

Among the species, Syngonium (P_2) produced the most suckers (2.56), followed by Pandanus (P_3) with 2.28, while Philodendron (P_1) recorded the lowest (1.23). Interaction effects were also significant, with N_2P_2 (Syngonium + 19:19:19 @ 2 g/L + micronutrient spray @ 4 g/L) showing the maximum number of suckers (3.45), followed by N_1P_2 (3.11). The minimum number (0.82) was recorded in N_3P_1 (Philodendron with fertilizer stick).

These findings suggest that a combination of readily available macronutrients through fertigation and targeted micronutrient foliar application significantly enhances sucker production. The superior performance of N_2 may be attributed to the higher concentration of NPK, particularly potassium, which plays a pivotal role in carbohydrate translocation and cell division, both essential for lateral bud activation and sucker initiation (14). Moreover, micronutrient foliar spray likely improved nutrient assimilation efficiency, especially under vertical growing conditions where root zone volume and uptake potential are restricted.

The species-specific response can be linked to inherent physiological traits. Syngonium, a fast-growing vine with an active meristematic base, is naturally predisposed to prolific vegetative propagation. In contrast, Philodendron, while ornamental, has a slower sucker initiation rate due to its compact and less spreading growth habit.

Current study's results align with previous studies which also reported that combined NPK and micronutrient application significantly enhances sucker formation in ornamental species (5, 15, 16),. These studies emphasized the role of micronutrients in regulating enzyme activity and growth hormone synthesis, both critical for vegetative offshoot development.

Root parameters

Dry weight of root (g)

At 180 DAP (2022 - 23 and 2023 – 24), maximum dry weight of root (0.469 g) was recorded in the treatment N_2- 19:19:19 at 2g /l + micronutrient spray at 4g / l followed by N_1- 19:19:19 at 2g /l + micronutrient spray at 2g / l (0.388 g). Whereas the N_3- one fertilizer stick / pot registered significantly minimum dry weight of root (0.279 g) (Table 4). There was significant difference among ornamental foliage plants on dry weight of root at 180 DAP. The maximum dry weight of root (0.589 g) was recorded with P_2- Syngonium followed by P_1-Philodendron (0.374 g). Whereas the minimum dry weight of root (0.151 g) was noticed with P_3- Pandanus. In the interactions, N_2P_2- 19:19:19 at 2g /l + micronutrient spray at 4g / l + Syngonium recorded significantly maximum dry weight of root (0.737 g) followed by N_1P_2- 19:19:19 at 2g /l + micronutrient spray at 2g / l + Syngonium (0.638 g). Whereas N_3P_1- one Fertilizer stick / pot + Pandanus noticed minimum dry weight of root (0.122 g).

Root length (cm)

At 180 DAP (2022 - 23 and 2023 – 24), the maximum root length (19.12 cm) which recorded with N_2- 19:19:19 at 2g /l + micronutrient spray at 4g / l, followed by N_1- 19:19:19 at 1g /l + micronutrient spray at 2g / l (17.66 cm). Whereas N_3- one fertilizer stick / pot recorded significantly minimum root length (13.58 cm) (Table 4). Significant difference among different ornamental foliage plants was reported with respect to root length at 180 DAP. The maximum root length (24.66 cm) was recorded with P_2- Syngonium followed by P_1-Philodendron (13.20 cm). Minimum root length (12.06 cm) was observed with P_3- Pandanus. In the interactions, N_2P_2- 19:19:19 at 2g / l + micronutrient spray at 4g / l + Syngonium recorded significantly

Table 3. Effect of different nutrient compositions on survival per centage (%), number of suckers per plant at 180 DAP in vertical garden

Treatments	Survival percentage (%)				Number of suckers per plant			
	P_1	P_2	P_3	Mean	P_1	P_2	P_3	Mean
N_1	91.67	96.67	91.67	93.33	1.55	3.11	2.49	2.39
N_2	95.00	100.00	88.33	94.44	1.43	3.45	2.78	2.56
N_3	90.00	93.33	83.33	88.89	0.82	1.50	1.34	1.22
N_4	95.00	96.67	88.33	93.33	1.11	2.16	2.50	1.93
Mean	92.92	96.67	87.92		1.23	2.56	2.28	
	S.Em ±		CD (5 %)		S.Em ±		CD (5 %)	
Ornamental foliage plants (P)	1.23		3.58		0.04		0.10	
Nutrient compositions (N)	1.42		4.13		0.04		0.12	
PXN	2.45		7.16		0.07		0.21	

Factor I: Ornamental foliage plants (P)- **P1**- Philodendron **P2**- Syngonium **P3**- Pandanus

Factor II: Nutrient compositions (N)-

N1: 19:19:19 @ 1g / l + micronutrient spray @ 2g / l

N2: 19:19:19 @ 2g / l + micronutrient spray @ 4g / l

N3: 1 fertilizer stick / pot

N4: 19:19:19 @1g / l

Table 4. Effect of different nutrient compositions on dry weight of root (g), root length (cm)cat 180 DAP in vertical garden

Treatments	Dry weight of root (g)				Root length (cm)			
	P_1	P_2	P_3	Mean	P_1	P_2	P_3	Mean
N_1	0.374	0.638	0.152	0.388	14.31	26.03	12.63	17.66
N_2	0.485	0.737	0.185	0.469	15.80	27.79	13.78	19.12
N_3	0.282	0.433	0.122	0.279	10.22	20.63	9.88	13.58
N_4	0.354	0.547	0.145	0.349	12.46	24.21	11.94	16.20
Mean	0.374	0.589	0.151		13.20	24.66	12.06	

	Dry weight S.Em ±	Dry weight CD (5 %)	Root length S.Em ±	Root length CD (5 %)
Ornamental foliage plants (P)	0.01	0.02	0.14	0.41
Nutrient compositions (N)	0.01	0.02	0.16	0.47
PXN	0.01	0.04	0.28	0.81

Factor I: Ornamental foliage plants (P)- **P1**- Philodendron **P2**- Syngonium **P3**- Pandanus

Factor II: Nutrient compositions (N)-

N1: 19:19:19 @ 1g / l + micronutrient spray @ 2g / l

N2: 19:19:19 @ 2g / l + micronutrient spray @ 4g / l

N3: 1 fertilizer stick / pot

N4: 19:19:19 @1g / l

maximum root length (27.79 cm) followed by N_1P_2- 19:19:19 at 2g /l + micronutrient spray at 2g / l + Syngonium (26.03 cm). While N_3P_3- 1 fertilizer stick / pot + Philodendron recorded minimum root length (9.88).

The application of NPK fertilizers, particularly when combined with micronutrients, significantly enhanced both the dry weight of roots and length of roots. Nitrogen (N) fosters overall plant growth, including root expansion, by boosting protein synthesis and cell division. Phosphorus (P) supports root development through the formation of a robust root system and efficient energy transfer. Potassium (K) aids in regulating water uptake and enzyme activation, which further enhances root health. Micronutrients contribute to increased root biomass by participating in various metabolic processes such as enzyme activation and photosynthesis (17). While they do not directly affect root growth, they support overall plant health and metabolic functions that indirectly benefit root elongation. Micronutrients like zinc and copper are crucial for enzyme functions that facilitate root development (18, 19). Overall, the combined effect of NPK fertilizers and micronutrients results in a stronger, more extensive root system, which is reflected in both higher dry weight and increased root length.

Soil parameters

Nutrient compositions pH before planting and at end of the experiment

Table 5 provides pH and Electrical Conductivity (EC) values for different nutrient composition treatments before planting and at the end of the experiment. All treatments showed an increase in pH by the end of the experiment, indicating a shift towards more alkaline conditions. The treatment with N_1-19:19:19 @ 1g/lit + micronutrient @ 2g/lit exhibited the largest increase in pH (6.08 to 7.27 in first season and 6.06 to 7.31 in second season), suggesting that this particular combination may significantly influence the pH levels in the growing media.

Nutrient compositions EC before planting and at end of the experiment.

Across all treatments, a noticeable increase in electrical conductivity (EC) was observed from before planting to the end of the experiment, indicating a gradual accumulation of soluble salts in the growing media. Among treatments, the fertilizer stick (N_3) recorded the highest final EC (2.84 dS/m), suggesting a potential risk of salt buildup in confined vertical systems. In vertical gardens, where the media volume is limited and natural leaching is minimal, such salt accumulation can lead to osmotic stress, reduced water uptake and eventual decline in plant health-particularly over longer durations.

In contrast, N_2 (19:19:19 @ 2 g/L + micronutrient spray @ 4 g/L) showed moderate increases in both EC and pH, reflecting a balanced nutrient uptake and minimal residual salt accumulation, making it more suitable for sustained use in vertical setups. This is likely due to the water-soluble nature of the fertigation system that allows for more even nutrient distribution and some leaching, reducing salt retention in the root zone. Interestingly, N_1 (lower-dose NPK + micronutrients) showed a greater increase in pH, which may indicate overcompensation from base-forming nutrients or a shift in media buffering capacity. Although the EC was lower than in N3, the altered pH could still affect nutrient availability over time, especially for micronutrients like iron and manganese, which are sensitive to alkaline conditions. N_4 (NPK without micronutrients) showed modest increases in both EC and pH, but the absence of micronutrients may lead to subclinical nutrient deficiencies over time, even if salt stress is not immediate.

These findings underscore the importance of nutrient source selection and delivery method in vertical gardens, where the

Table 5. Different variation of pH and EC in nutrient compositions in before planting and end of the experiment

Nutrient compositions	Ph 2022-2023		EC (ds/m) 2022-2023		pH 2023-2024		EC (ds/m) 2023-2024	
	Before planting	At end of the experiment	Before planting	At end of the experiment	Before planting	At end of the experiment	Before planting	At end of the experiment
N_1: 19:19:19 @ 1g / l + Micronutrient spray @ 2g / l	6.08	7.27	1.51	2.44	6.06	7.31	1.52	2.48
N_2: 19:19:19 @ 2g / l+ Micronutrient spray @ 4g / l	6.22	7.10	1.27	2.5	6.25	7.14	1.31	2. 11
N_3: 1 Fertilizer Stick / pot	6.3	6.93	1.3	2.84	6.27	6.98	1.35	2.86
N_4: 19: 19: 19 @ 1g / l	6.11	7.06	1.48	2.37	6.15	7.15	1.52	2.89

confined media, restricted drainage and layered root zones make systems particularly vulnerable to salt buildup and pH imbalance. Slow-release fertilizers, while convenient, can lead to uneven nutrient availability and salt accumulation near the surface or in the lower tiers, which can compromise plant vigor and longevity.

In contrast, fertigation combined with foliar micronutrients (as in N_2) appears to offer better control over nutrient dynamics, helping to prevent excess accumulation while still supporting optimal growth. For long-term vertical installations, particularly those in urban environments with limited maintenance, managing EC and pH through balanced, soluble nutrient applications is critical to maintaining plant health and system sustainability.

Conclusion

The present study demonstrates that balanced nutrient management, specifically the combination of 19:19:19 at 2 g/L with micronutrient foliar spray at 4 g/L, significantly enhances the vegetative and root growth of ornamental foliage plants under vertical gardening conditions. Among the tested species, Syngonium podophyllum exhibited superior adaptability, root vigor and survival, indicating its potential as a model foliage plant for vertical systems. The findings suggest that nutrient formulations combining readily available macronutrients with targeted foliar micronutrient applications can overcome the spatial and root volume limitations typical of vertical gardens, promoting uniform growth and sustained aesthetic quality. While the results largely align with established knowledge on the role of NPK and micronutrients in plant development, the novelty of this study lies in its application to confined, vertical growing systems an emerging urban horticultural setting where nutrient and water retention dynamics differ substantially from traditional containers or beds. The findings highlight that nutrient concentration and mode of delivery must be optimized not only for species performance but also for system efficiency and long-term maintenance. From a practical standpoint, the study recommends the use of soluble fertigation-based nutrient delivery systems combined with periodic micronutrient foliar sprays for vertical installations. This approach minimizes salt accumulation, ensures consistent nutrient availability and supports plant survival with minimal maintenance making it suitable for commercial urban landscaping and indoor greening projects. However, the study was limited to short-term (180-day) observations and three species under semi-shade conditions. Future research should examine the long-term nutrient dynamics, media sustainability and physiological stress responses under variable light, temperature and irrigation regimes. Additionally, integrating sensors for monitoring EC and moisture could help design precision nutrient delivery systems tailored for vertical horticulture. Overall, the study provides foundational insights for nutrient optimization in ornamental foliage plants grown vertically, bridging the gap between traditional plant nutrition research and its application in space-efficient, sustainable urban horticulture.

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Authors' contributions

BS conducted the experiment, drafted the manuscript; PP planned the experiment, edited and reviewing of manuscript; ZS conceptualized and designed the experiment, edited and reviewed the manuscript; GJ and PK planned and coordinated the work, reviewing of manuscript. All authors have read and agreed to the published version of the manuscript.

Compliance with ethical standards

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