Research Article

Effect of Organic Fertilization and Foliar Nutrient Sprays on Enhancing Vegetative Growth and Chemical Attributes of Local Sweet Lemon Saplings

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Abstract | The study evaluated the effects of soil application of spent mushroom substrate at rates of 0, 1, and 2 kg sapling^{-1}, foliar spraying with potassium sulfate at 0 and 3 g L^{-1}, and foliar application of amino acids at three concentrations (0, 2, and 4 milliliters per liter) on the vegetative growth of local sweet lemon saplings. Treatments were implemented in a randomized complete block design (RCBD) with three replicates as a factorial experiment. The results showed that soil fertilization with spent mushroom substrate at the highest level (M_2) and foliar amino acids at 4 mL L^{-1} (A_2) improved vegetative growth, leaf zinc and manganese contents, and the C/N ratio. Foliar potassium sulfate at 3 g L^{-1} (K_1) increased leaf number and leaf zinc content. The interaction treatment $M_2K_0A_2$ outperformed other combinations by giving the greatest increase in stem diameter (2.43 mm), the highest number of branches (5.57 branches sapling^{-1}), and the highest C/N ratio (5.19). The combination $M_2K_1A_2$ produced the greatest increase in leaf number (99.57 leaves sapling^{-1}) and the highest leaf concentrations of zinc (94.73 mg kg^{-1}) and manganese (32.87 mg kg^{-1}). In contrast, the control treatment ($M_0K_0A_0$ — no amendments) consistently yielded the lowest values across all measured parameters.

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Introduction

Citrus species belong to the Rutaceae family, which encompasses numerous genera distributed across tropical and subtropical regions between 40° N and 40° S. Citrus are evergreen fruit trees, generally small to medium in size, characterized by oil glands in their leaves that impart a distinctive aromatic scent (Al-Khafaji *et al*., 1990; Latif and Abood, 2022). Among the most important genera is *Citrus*, which includes many species of high economic importance and notable nutritional value (Hashash and Ben Hamouda, 2022). Citrus fruits are rich in beneficial constituents such as potassium, phosphorus, calcium, and pectin, in addition to vitamin C and the B-vitamin complex (Topi, 2020). The center of origin of citrus is believed to be Southeast Asia, including India, China, and the Malay Archipelago (Abobatta and El-Azazy, 2020). Within *Citrus*, sweet lemon *Citrus limetta*—also known locally as "al-banzahir al-hulw"—includes an Iraqi cultivar noted for earliness, high yield, and good fruit quality (Al-Khafaji *et al*., 1990). In 2023, global production reached 21,843,162.86 tons from 1,388,251 hectares; India ranked first, followed by Mexico, China, Turkey, and Argentina, while Sudan led the Arab world and ranked thirteenth globally, followed by Egypt (FAO, 2023; Mohammed *et al*., 2025).

The intensive use of chemical fertilizers and pesticides has adversely affected natural and environmental balance, underscoring the need for modern strategies to improve fertilizer-use efficiency—whether organic or mineral (Wan *et al*., 2021; Salloom *et al*., 2023). Organic fertilizers improve soil quality by enhancing its structure, water retention, aeration, and microbial activity. Additionally, they offer a gradual release of vital nutrients like nitrogen, phosphorus, and potassium. Moreover, these fertilizers assist plants in coping with various environmental challenges such as drought, salinity, and extreme temperatures. By reducing reliance on chemical fertilizers and limiting environmental pollution, organic fertilization supports sustainable agriculture and long-term soil health (Mwangi *et al*., 2024; Moghith, 2024).

Among the organic amendments utilized is spent mushroom substrate (SMS)—the residual material remaining after harvesting edible or medicinal mushroom fruiting bodies. Typical SMS blends include four principal components: straw, animal-origin organic materials, gypsum powder (calcium sulfate dihydrate, $CaSO_4{\cdot}2H_2O$), and clean water; it is the major by-product of mushroom cultivation (Uzun, 2004; Martín *et al*., 2023). In parallel, foliar fertilization has emerged as more efficient and sustainable alternative for improving nutrient use efficiency, crop yield, and quality. Combining soil and foliar fertilization can reduce chemical fertilizer inputs while maintaining strong yields and returns; it is therefore considered an effective approach to mitigate salinity and improve the soil environment (Niu *et al*., 2021). Accordingly, this study employed foliar potassium and amino acids.

Potassium (K) is the second most important plant nutrient after nitrogen. It plays a central role in plant growth and development by mediating nutrient transport, activating enzymes, regulating stomatal function, and enhancing tolerance to environmental stresses—properties that are pivotal for sustainable agricultural productivity and high-quality returns (Rawat *et al*., 2022; Khan and Nabi, 2023). Amino acids likewise perform vital functions in plant physiology, contributing to osmotic regulation, detoxification, stress tolerance, nutrient uptake, vitamin biosynthesis, secondary metabolism, and antioxidant enzyme activity. Act as biostimulants, i.e., They increase the growth of plant, enhance its value with respect to nutrition and can manage abiotic stresses *in vivo*; boost nitrogen uptake and root development along with boosting antioxidant protection. In addition, amino acids can improve of plant K content in normal and stressful conditions. For the current study the commercial product Wuxal Amino, which is derived from natural materials and contains amino acids (proline, alanine, glycine, and threonine), was used (Baqir *et al*., 2019; Kheir *et al*., 2021; Jahanbani, *et al*., 2024).

To find effective nutritional practices that can improve the production of healthy seedlings capable of achieving better growth and quality, this study was set up. Additionally, this study aimed to assess the effect of fertilization with spent mushroom substrate and foliar sprays of potassium and amino acids on improving the vegetative growth and chemical properties of local sweet lemon saplings.

Materials and Methods

The research was conducted at Research Station (B), College of Agricultural Engineering Sciences, University of Baghdad, throughout the spring growing season from 15th February 2024 to 15th December 2024. The experiment evaluated the effects of soil application of spent mushroom substrate (SMS) and foliar sprays of potassium sulfate and amino acids on local sweet lemon saplings (*Citrus limetta*).

One-year-old, growth-uniform saplings of the local sweet lemon cultivar, grafted onto sour orange rootstock, were procured from the certified Karbala Citrus Nursery (Horticulture Directorate, Al-Hindiyah, Karbala). On 15 February 2024, saplings were transplanted into 26-cm diameter pots (capacity 7 kg) filled with a river silt: peat moss mixture at a ratio of 1:2 (v/v).

A three-factor factorial arrangement was used:

Factor 1 – Spent mushroom substrate (SMS) as a soil amendment

- **M_0:** No addition
- **M_1:** 1 kg sapling^{-1}
- **M_2:** 2 kg sapling^{-1}

Factor 2 – Foliar potassium (as potassium sulfate)

- **K_0:** No spray
- **K_1:** 3 g L^{-1}

Factor 3 – Foliar amino acids (commercial product: Wuxal Amino)

The product is derived from natural sources and contains **proline, alanine, glycine, and threonine**, in addition to **nitrogen**.

- **A_0:** No spray
- **A_1:** 2 mL L^{-1}
- **A_2:** 4 mL L^{-1}

Treatments were allocated to the experimental units using a randomized complete block design in a factorial arrangement, with three replications, and three saplings per experimental unit, for a total of 162 saplings. Foliar applications were made every two weeks from 1 March 2024 to 1 July 2024, then resumed on 1 September 2024 and continued until 15 November 2024.

All vegetative growth measurements were recorded at the beginning and end of the experiment; the increase during the experimental period was calculated for each trait:

Increase in stem diameter (mm): measured using a Vernier caliper.

Increase in number of lateral branches (branches sapling^{-1}): lateral branches were counted per sapling at the start and end; averages were computed per treatment.

Increase in number of leaves (leaves sapling^{-1}): leaves were counted per sapling at the start and end; averages were computed per treatment.

Leaf manganese content (mg kg^{-1}): determined by Atomic Absorption Spectrophotometry following Estefan *et al.* (2013).

Leaf zinc content (mg kg^{-1}): determined in the digestion solution by Atomic Absorption Spectrophotometry following Estefan *et al.* (2013).

C/N Ratio in Branches: Calculated by dividing the total carbohydrates (%) by the % of total nitrogen in branch tissues.

Data were analyzed according to the factorial RCBD. Treatment means were compared using the least significant difference (LSD) test at $p \leq 0.05$, following (Elsahooki and Wahib, 1990). Spraying was carried out every two weeks, starting from March 1, 2024, until July 1, 2024, and repeated from September 1, 2024, until November 15, 2024.

Results

Average increase in stem diameter (mm)

Table 1 indicates significant differences among spent mushroom substrate (SMS) levels for stem diameter increase: the highest mean was at M_2 (2.23 mm). For amino-acid sprays, A_2 outperformed other levels with an increase of 2.17 mm. In contrast, spraying with potassium sulfate did not significantly affect this trait.

Table 1: *Effect of fertilization with spent mushroom bedding residues and foliar spraying of potassium sulfate and amino acids on the rate of increase in stem diameter (mm) of local sweet lemon saplings.*

M	K	A			M × K
		A_0	A_1	A_2	
M_0	K_0	1.47	1.60	1.67	1.58
	K_1	1.60	1.80	1.87	1.76
M_1	K_0	1.63	2.07	2.33	2.01
	K_1	2.10	2.03	2.33	2.16
M_2	K_0	2.10	2.20	2.43	2.24
	K_1	1.93	2.33	2.40	2.22
L.S.D. 0.05		0.570			0.329
M x A					
M_0		1.53	1.70	1.77	1.67
M_1		1.87	2.05	2.33	2.08
M_2		2.02	2.27	2.42	2.23
L.S.D. 0.05		0.403			0.232
K x A					
K_0		1.73	1.96	2.14	1.94
K_1		1.88	2.06	2.20	2.04
L.S.D. 0.05		0.329			N. S
A		1.81	2.01	2.17	
L.S.D. 0.05		0.232			

For the two-way interaction between SMS and potassium, treatment M_2K_0 achieved a mean increase of 2.24 mm. A significant response also appeared in the SMS × amino acids interaction, where M_2A_2 produced the greatest increase (2.42 mm). In the potassium × amino acids interaction, K_1A_2 yielded 2.20 mm.

Table 2: *Effect of fertilization with spent mushroom bedding residues and foliar spraying of potassium sulfate and amino acids on the rate of increase in the number of lateral branches (branches sapling^{-1}) of local sweet lemon saplings.*

M	K	A			M × K
		A_0	A_1	A_2	
M_0	K_0	2.20	2.57	3.00	2.59
	K_1	2.87	3.67	3.90	3.48
M_1	K_0	3.67	3.23	5.20	4.03
	K_1	3.77	4.13	4.47	4.12
M_2	K_0	3.77	4.37	5.57	4.57
	K_1	3.57	4.87	5.33	4.59
L.S.D. 0.05		0.985			0.568
M x A					
M_0		2.53	3.12	3.45	3.03
M_1		3.72	3.68	4.83	4.08
M_2		3.67	4.62	5.45	4.58
L.S.D. 0.05		0.696			0.402
K x A					
K_0		3.21	3.39	4.59	3.73
K_1		3.40	4.22	4.57	4.06
L.S.D. 0.05		0.568			N. S
A		3.31	3.81	4.58	
L.S.D. 0.05		0.402			

Considering the three-way interaction, $M_2K_0A_2$ recorded the maximum increase in stem diameter (2.43 mm), compared with the lowest value in the control $M_0K_0A_0$ (1.47 mm).

Increase in the number of lateral branches (branches sapling^{-1})

Table 2 shows significant effects of spent mushroom substrate (SMS) and amino-acid sprays on branching, while potassium sulfate alone did not alter this trait. The highest mean increase in branch number occurred with M_2 (4.58 branches sapling^{-1}). For amino acids, A_2 likewise produced the greatest increase (4.58 branches sapling^{-1}).

The interaction between soil fertilization with spent mushroom substrate and foliar spraying with potassium sulfate positively influenced branching, as the combined treatment M_2K_1 yielded the highest branch increase of 4.59 branches sapling^{-1}. The two-way interaction SMS × amino acids clearly outperformed the other combinations, reaching an increase of 5.45 branches sapling^{-1}. The interaction between the spraying treatments with potassium sulfate and spraying with amino acids also had a significant effect on increasing the number of branches, as the interaction treatment K_0A_2 gave the highest increase of 4.59 branches sapling^{-1}.

Table 3: *Effect of fertilization with spent mushroom bedding residues and foliar spraying of potassium sulfate and amino acids on the number of leaves (leaves sapling^{-1}) of local sweet lemon saplings.*

M	**K**	**A**			**M × K**
		A_0	A_1	A_2	
M0	K_0	53.67	55.67	62.23	57.19
	K_1	60.07	59.00	70.97	63.34
M1	K_0	60.70	81.87	81.67	74.74
	K_1	83.97	90.87	95.23	90.02
M2	K_0	70.47	75.00	78.67	74.71
	K_1	73.67	86.83	99.57	86.69
L.S.D. 0.05		5.480			3.164
M x A					
M_0		56.87	57.33	66.60	60.27
M_1		72.33	86.37	88.45	82.38
M_2		72.07	80.92	89.12	80.70
L.S.D. 0.05		3.875			2.237
K x A					
K_0		61.61	70.84	74.19	68.88
K_1		72.57	78.90	88.59	80.02
L.S.D. 0.05		3.164			1.827
A		67.09	74.87	81.39	
L.S.D. 0.05		2.237			

For the three-way interaction, $M_2K_0A_2$ achieved the maximum branch increase (5.57 branches sapling^{-1}), whereas the control $M_0K_0A_0$ recorded the lowest value (2.20 branches sapling^{-1}).

Average increase in the number of leaves (leaves sapling−1)

The results in Table 3 revealed statistically significant differences among the levels of soil fertilization with spent mushroom substrate (SMS), where treatment M_1 (1 kg SMS sapling^{-1}) outperformed all others, achieving the highest rate of leaf number increase at 82.38 leaves sapling^{-1}. Potassium sulfate spray also had a positive and significant effect, with treatment K_1 yielding the highest average increase of 80.02 leaves sapling-1. Similarly, amino acid spraying treatments showed significant superiority, with treatment A_2 (4 mL L^{-1}) yielding the highest value for this trait at 81.39 leaves sapling^{-1}. The two-way interactions, results indicated that interactions significantly influenced the rate of leaf number increase. The SMS × potassium interaction showed that M1K1 achieved an increase of 90.02 leaf sapling^{-1}. For SMS × amino acids, the M_2A_2 combination clearly outperformed the others, with 89.12 leaf sapling^{-1}. The potassium × amino acids interaction was also significant; K_1A_2 produced an increase of 88.59 leaf sapling^{-1}. Considering the three-way interaction, $M_2K_1A_2$ recorded the maximum increase in leaf number at 99.57 leaf sapling^{-1}, whereas the control treatment $M_0K_0A_0$ produced the lowest value at 53.67 leafsapling^{-1}.

Table 4: *Effect of fertilization with spent mushroom bedding residues and foliar spraying of potassium sulfate and amino acids on leaf manganese content (mg kg^{-1}) of local sweet lemon saplings.*

M	K	A			M × K
		A_0	A_1	A_2	
M_0	K_0	22.50	23.73	24.57	23.60
	K_1	24.10	25.50	26.40	25.33
M_1	K_0	24.13	27.00	30.00	27.04
	K_1	30.07	27.33	28.33	28.58
M_2	K_0	27.57	30.13	30.03	29.24
	K_1	30.83	31.13	32.87	31.61
L.S.D. 0.05		1.309			0.756
M x A					
M_0		23.30	24.62	25.48	24.47
M_1		27.10	27.17	29.17	27.81
M_2		29.20	30.63	31.45	30.43
L.S.D. 0.05		0.926			0.534
K x A					
K_0		24.73	26.96	28.20	26.63
K_1		28.33	27.99	29.20	28.51
L.S.D. 0.05		0.756			0.436
A		26.53	27.47	28.70	
L.S.D. 0.05		0.534			

Manganese content of leaves (mg kg-1)

According to the results presented in Table 4, the addition of spent mushroom substrate (SMS) at different levels significantly outperformed other treatments. The highest manganese content in leaves was in treatment M_2, reaching 30.43 mg kg-1. Potassium sulfate spray treatments significantly outperformed the treatment K_1, reaching 28.51 mg kg-1. Likewise, amino-acid sprays significantly raised manganese content; the maximum value was recorded at A_2 (28.70 mg kg^{-1}).

For the two-way interactions, SMS × potassium was significant: M_2K_1 yielded the highest manganese content (31.61 mg kg^{-1}). In the SMS × amino acids interaction, M_2A_2 increased leaf manganese to 31.45 mg kg^{-1}. The potassium × amino acids interaction was also significant, with K_1A_2 giving 29.20 mg kg^{-1}.

Table 5: *Effect of spent mushroom substrate fertilization and foliar sprays of potassium sulfate and amino acids on leaf zinc content (mg kg^{-1}) of local sweet lemon saplings.*

M	K	A			M × K
		A_0	A_1	A_2	
M_0	K_0	75.50	77.33	77.40	76.74
	K_1	77.10	77.37	80.23	78.23
M_1	K_0	80.30	81.47	82.43	81.40
	K_1	84.20	84.40	85.23	84.61
M_2	K_0	80.47	85.40	85.57	83.81
	K_1	86.00	92.33	94.73	91.02
L.S.D. 0.05		1.956			1.129
M x A					
M_0		76.30	77.35	78.82	77.49
M_1		82.25	82.93	83.83	83.01
M_2		83.23	88.87	90.15	87.42
L.S.D. 0.05		1.383			0.799
K x A					
K_0		78.76	81.40	81.80	80.65
K_1		82.43	84.70	86.73	84.62
L.S.D. 0.05		1.129			0.652
A		80.59	83.05	84.27	
L.S.D. 0.05		0.799			

The three-way interaction produced the greatest overall manganese content in leaves when SMS, potassium sulfate, and amino acids were combined: $M_2K_1A_2$ reached 32.87 mg kg^{-1}, compared with the lowest value in the control $M_0K_0A_0$ (22.50 mg kg^{-1}).

Leaf zinc content (mg kg^{-1})

Table 5 shows that applying spent mushroom substrate (SMS) significantly increased leaf zinc content across levels, with the highest value at M_2 (87.42 mg kg^{-1}). Foliar potassium sulfate and amino-acid sprays each produced significant main effects as well, reaching 84.62 mg kg^{-1} at K_1 and 84.27 mg kg^{-1} at A_2, respectively. Two-way interactions were also significant: M_2K_1, M_2A_2, and K_1A_2 achieved the greatest zinc contents—91.02, 90.15, and 86.73 mg kg^{-1}, respectively. The three-way interaction further elevated zinc accumulation: the combination $M_2K_1A_2$ recorded the highest overall leaf zinc content (94.73 mg kg^{-1}), while the control $M_0K_0A_0$ showed the lowest (75.50 mg kg^{-1}).

Carbohydrate-to-nitrogen ratio (C/N ratio) in shoots

The results in Table 6 show significant superiority across the different levels of fertilization with spent mushroom substrate fertilizer, with the highest ratio for this trait reaching 4.55 in treatment M_2. Foliar potassium sulfate also had a significant main effect, reaching 4.42 at K_1, whereas amino-acid levels did not differ significantly.

Table 6: *Effect of spent mushroom substrate fertilization and foliar sprays of potassium sulfate and amino acids on the C/N ratio of local sweet lemon saplings.*

M	K	A			M × K
		A_0	A_1	A_2	
M_0	K_0	4.06	3.40	4.05	3.836
	K_1	4.59	4.05	4.37	4.335
M_1	K_0	3.76	4.17	4.01	3.98
	K_1	4.08	4.37	4.77	4.41
M_2	K_0	4.09	4.41	5.19	4.57
	K_1	4.66	4.58	4.34	4.53
L.S.D. 0.05		0.735			0.424
M x A					
M_0		4.33	3.72	4.21	4.09
M_1		3.92	4.27	4.39	4.19
M_2		4.38	4.49	4.76	4.55
L.S.D. 0.05		0.519			0.244
K x A					
K_0		3.97	3.99	4.42	4.13
K_1		4.45	4.33	4.49	4.42
L.S.D. 0.05		0.424			0.652
A		4.21	4.16	4.45	
L.S.D. 0.05		N.S			

The results of the two-way interaction showed that the interaction had a significant effect on increasing C/N ratio. The SMS × potassium interaction showed that M_2K_0 yielded the highest ratio (4.57). For SMS × amino acids, M_2A_2 produced 4.76. The potassium × amino acids interaction was likewise significant, with K_1A_2 reaching 4.49. In the three-way interaction, $M_2K_0A_2$ gave the maximum C/N ratio (5.19), compared with the lowest value observed at $M_0K_0A_1$ (3.40).

Discussion

The above results revealed that there was a significant increase in all the vegetative traits including leaf number, stem diameter, number of laterals branches, and zinc and manganese content of leaves. This enhancement is due to the positive impact of SMS in enhancing physicochemical soil characteristics (aeration and moisture holding capacity) as well as microbiological activity, microbial-mediated processes with nutrients available for plant uptake (Othman *et al*., 2020). This in turn leads to better nutrient intake and increased photosynthetic rate, mainly by increasing chlorophyll and magnesium-bound nitrogen plant proteins. This accounts for the marked increase in the leaf number, the branch number and stem diameter (Iglesias *et al*., 2025 and Demir, 2017). SMS is rich in bioactive metabolites including amino acids, vitamins and enzymes that boost cell division and elongation of growth zones (Mohd Hanafi *et al*., 2018). This may attribute to the decomposition of organic substances derived from the SMS decomposition which work as chelating agents and contribute to elements (Zn and Mn) release, hence their increasing available in the plant. SMS contributed to an increase in carbohydrate accumulation and an improvement in nitrogen content in the branches, which was reflected in an enhanced C/N ratio. This is attributed to the degradable organic matter present in SMS (Fidanza *et al*., 2010), which stimulates the activity of soil microorganisms (Pintarič *et al*., 2024). The resulting increase in microbial activity enhances the biodegradation efficiency of the organic matter in SMS, thereby improving the carbon–nitrogen balance and ultimately leading to a more favorable C/N ratio. which is associated with an increase in the plant's physiological efficiency in metabolic processes. (Majeed and Abood, 2021). This is consistent with what It was reached by (Ebakivie, 2022; Hassouni and Khalil., 2025; Tuhy *et al*., 2015; and (Al-Obaidi and Abdul-Ratha, 2021). Potassium is an essential element in regulating the opening and

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closing of stomata, and activating a large number of enzymes, most of which contribute to cell division processes, which leads to the elongation of the stem and leaves, improving the efficiency of photosynthesis, improving root activity, and increasing the internal transport of elements within the plant, which has a positive effect on the vegetative growth of the plant (plant height, increased number of leaves, and leaf content of zinc and manganese (Silva and Uchida, 2000; Pandey and Mahiwal, 2020). It also contributes to enhancing nutrient uptake efficiency through its direct effect on membranes permeability and the activation of nitrate transport (Toor *et al*., 2021). It also alleviates osmotic stress and increases the plant's ability to translocate carbohydrates from the leaves to the growing tissues in the branches (Ennab & Khedr, 2021). which enhances the efficiency of N absorption and its utilization in the building of proteins and bioactive compounds (Toor *et al*., 2021) and increases the percentage of carbohydrates in the branches (Lo'ay *et al*., 2021), thus modifying the C/N ratio in a direction that reflects high metabolic efficiency (Toor *et al*., 2021). This is in agreement with (Sun *et al*., 2023; Mohammed and Majeed, 2024; Khalil and Hammoodi, 2021; and Saaseea and Al-a'amry, 2023). Amino acids function as biostimulants that improve photosynthetic efficiency ,nutrient acquisition and Activation of sugar formation(Al-Saif *et al*., 2024). They further promote the uptake of macro- and microelements as chelating agents for microelements, and the formation of chlorophyll, It also participate in regulating chlorophyll synthesis and activating enzymes associated with carbon metabolism, thereby enhancing sugar production and promoting the growth of vegetative tissues, This is directly reflected in the growth of leaves and the increase in their number and content of Zinc and manganese (Kawade *et al*., 2023; Rahman *et al*., 2024; Muhammad and Latif, 2022), which is consistent with Mariush and Al-Mharib, 2020; Jaff and Medan, 2024; Saaseea and Al-a'amry, 2024 and Al-Hayani and Al-Hadethi, 2023).

Conclusions

The application of 2 kg per seedling of spent mushroom substrate (SMS), combined with foliar spraying of amino acids (4 mL L^{-1}) and potassium sulfate (3 g L^{-1}) — treatment $M_2K_1A_2$ — resulted in significant and clear improvements in stem diameter, leaf number, and leaf content of manganese and zinc (2.40 mm, 99.57 leaves per seedling, 32.87 mg kg^{-1} Mn, and 94.73 mg kg^{-1} Zn). Meanwhile, the three-way interaction treatment $M_2K_0A_2$ (2 kg SMS + no potassium + 4 mL L^{-1} amino acids) demonstrated a pronounced and statistically significant effect on lateral branch number and C/N ratio (5.57 branches per seedling and 5.19, respectively).

Therefore, it is recommended to adopt an integrated fertilization program that combines spent mushroom substrate (2 kg per seedling), amino acids (4 mL L^{-1}), and potassium sulfate (3 g L^{-1}) to maximize leaf production and enhance leaf micronutrient content (Zn, Mn) as well as stem thickening. Alternatively, omitting potassium sulfate from the program (i.e., using $M_2K_0A_2$) is recommended when the primary objective is to increase lateral branching and optimize the C/N ratio — both critical for structural development and physiological maturity. Such an integrated approach contributes to improved plant growth and supports the achievement of sustainable agricultural production.

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Novelty Statement

This study is the first, to our knowledge, to integrate spent mushroom substrate (SMS) with foliar potassium sulfate and amino acids to optimize nursery-stage performance of local sweet lemon (*Citrus limetta*) under lath-house conditions in Baghdad

Author's Contribution

Zainab Musa Jaffar: fieldwork, sowing, harvesting; wrote abstract, introduction, data collection, data entry in GenStat and analysis, results and discussion, conclusion and references.
Salah Hassan Jabbar AL-Hchami: Editing of draft, supervised the research, analyzed data, reviewed the manuscript, proofread, reviewed the manuscript, Overall Management of the article, performed proof-

reading, and revised the manuscript.

Generative AI and AI-assisted technology statement

The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest

The authors have declared no conflict of interest

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