

Sustainable practices utilizing arbuscular mycorrhizae and struvite for enhanced growth of *Solanum melongena* L.

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Abstract

The use of phosphorus (P) fertilizer derived from secondary P minerals, such as struvite recovered from waste streams, is often not well understood. However, it can be as effective as commercial P fertilizers, especially when combined with plant-associated microorganisms. This study examines the synergistic effect of struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$), a slow-release phosphorus fertiliser, and mycorrhizae, a biostimulant, on the growth and nutrient uptake in *Solanum melongena* L. across various growing media. The study comprised twelve distinct treatments, which included various combinations of soil and coco peat, with and without the incorporation of struvite and mycorrhizae. Plant growth parameters, encompassing height, leaf and flower count, stem girth, and yield, were systematically monitored from 30 to 120 days and subsequently analysed using ANOVA ($P < 0.05$) followed by DMRT at a 5% level. Although mycorrhizae implementation improved productivity in cocopeat by 9% to 27% (representing nearly a 130% increase relative to the unamended control), the lowest P residual was found in T8, which produced a maximum absolute yield of 88.33%—an approximate 17% increase over its respective unamended soil control. Our study suggests that the synergistic action between struvite and AMF contributed to improved fertiliser management.

Key words: Cocopeat, mycorrhizae, nutrient recovery, *Solanum melongena* L, struvite, fertilizer

Introduction

Phosphorus (P) is essential for plant growth and food production, but its availability is declining due to the depletion of non-renewable phosphate rock reserves, which are expected to run out within the next 50 to 100 years (Daneshgar *et al.*, 2018). This scarcity not only threatens global food security but also necessitates alternative strategies for phosphorus recovery and utilization. The recovery of phosphorus in the wastewater as struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$), a slow-release fertilizer, is one of the promising methods that could be used as a source of phosphorus in a sustainable form. Moreover, phosphorus runoff is also a contributing factor to eutrophication, which explains why sustainable sources and better efficiency in nutrient use are needed (Shaddel *et al.*, 2019). Struvite is a renewable product whose production is easy and does not create wastewater treatment challenges such as pipe clogging (Rahman *et al.*, 2014). Recovery of phosphorus as struvite in wastewater may provide an estimated 15-20 percent of the world phosphorus needs. Nevertheless, its application is effective in soils, types of crops and mode of application (Bindraban *et al.*, 2020). Struvite has a low solubility and mobility, so it is commonly co-associated with biostimulants, including P-solubilising bacteria (PSB) (Hernandez Jimenez *et al.*, 2020), earthworms (Ferron *et al.*, 2025), or arbuscular mycorrhizal fungi (AMF) to associate with the root (Liu *et al.*, 2016). Arbuscular Mycorrhizal Fungi (AMF) are symbiotic interactions that improve nutrient uptake by the plant root and complement phosphorus uptake (Kavatagi and Lakshman, 2014). Arbuscular mycorrhizal fungi (AMF) make

plants acquire otherwise inaccessible phosphorus by expanding the root network beyond the rhizosphere (Ossai, 2021).

Even though the advantages of AMF in seasonal plants with rock phosphates are well-reported, its combination with struvite is limited. Di Tomassi *et al.* (2021) examined the tomato growth in AMF with struvite, AMF with water-soluble monoammonium phosphate, and AMF with water and found that AMF enhanced the solubility of the struvite. Liu *et al.* (2016) examined the AMF response in calcareous soil treated with calcium superphosphate on two maize varieties, showing that AMF enhanced soil P availability and pH, although crop phenology influenced fertiliser P uptake. Other studies have shown mixed results, including AMF-induced growth suppression but significant changes in root exudation (Wen *et al.*, 2019). Despite the variability, exploring AMF-struvite interactions in phosphate management is crucial for understanding how arbuscular mycorrhizal fungi (AMF) enhance slow-releasing phosphorus (P) fertilisers in different media.

To investigate this integrated approach, *S. melongena* (eggplant) is an ideal model crop due to its high economic and nutritional value, as well as its responsiveness to fertilisers, making it relevant to horticulture (Bhatt *et al.*, 2022). Being a crop with high nutrient demand, it can be useful to investigate its relations with the growth media. It is adaptable to a wide range of climatic conditions thus making it an appropriate crop to be used in sustainable agriculture. Eggplant depends on phosphorus to develop and grow fruits and also it develops a beneficial relationship with arbuscular mycorrhizal fungi (AMF) (Khan *et al.*, 2019).

This paper is an analysis of the efficacy and synergy of struvite and AMF in the soilless cultivation sustainability. Coco peat is a potential substrate that is made by crushing coconut husks into coco peat, which offers high retention and aeration of water. In this study, three hypotheses were tested: (i) the availability of P in slow-release fertiliser in the soil and nutrient-limited Cocopeat. (ii) The fertilizing efficiency of struvite alone and struvite in combination with AMF will result in increased productivity and total P and N uptake. (iii) *S. melongena* growth will exhibit a positive response to struvite amendment, and this response will be further enhanced by the presence of AMF, an interaction not previously reported in this context. This study aims to demonstrate how AMF colonization interacts with phosphate fertilizers across different media.

Materials and methods

Struvite was recovered from the SRMIST University wastewater treatment plant. The precipitation process was conducted as a batch study by maintaining an optimal Mg:P:N ratio of 1:1:1 at pH 9.5. The 300 mL feedstock was stirred at 100 rpm at 25°C for 30–40 minutes, followed by settling. The precipitate was filtered, air-dried, and used in this study. Before planting, struvite, soil, cocopeat, and arbuscular mycorrhizal fungi (AMF) were thoroughly mixed to ensure uniform distribution and to assess how AMF influences phosphorus availability from struvite in different growing media. Struvite and AMF were tested both separately and in combination to evaluate their individual and synergistic effects on nutrient uptake and plant growth. This integration aimed to assess how AMF influences phosphorus availability from struvite in different growing media. Struvite and AMF were tested both separately and in combination to evaluate their individual and synergistic effects on nutrient uptake and plant growth. A pot experiment was conducted using a Completely Randomized Design (CRD) with three replications to cultivate brinjal. The potting media, comprising cocopeat, mycorrhizae, and *S. melongena* (var. PLR 1) seeds, was sourced from the Agricultural Department of the Government of Tamil Nadu. Standard agronomic practices were followed to ensure healthy crop growth.

The study was conducted at SRM Institute of Science and Technology, Kattankulathur (12.8230° N, 80.0444° E), to evaluate the fertilising efficiency of recovered struvite. Soil samples (0–15 cm depth) were collected, while soil and coco peat were sterilized and sun-dried for three hours to eliminate weeds, pests, and microorganisms. Physical and chemical properties were analysed according to the guidelines of the Tamil Nadu Agriculture Technology Information Centre (ATIC). The twelve treatments were designed to evaluate the individual and combined effects of struvite and mycorrhizae across different growing media. The details are in Table 1. Soil provides natural nutrients, while coco peat enhances nutrient retention with its fine structure and high water-holding capacity (25–30%). Their combination was tested for optimal nutrient absorption and plant growth. Struvite and mycorrhizae were tested separately and in combination to determine their individual contributions and potential synergies in enhancing phosphorus availability. Physicochemical parameters, including pH, electrical conductivity (EC), bulk density (BD), water-holding capacity (WHC), particle density (PD), porosity (Pt), and moisture content (MC), were assessed using standard procedures (Awang *et al.*, 2009; Kalaivani and Jawaharlal, 2019)

Table 1. Media combinations use for the study

Treatment	Combination
T1	Coco peat (C)
T2	Coco peat +struvite (C+ST)
T3	Coco peat + Mycorrhizae(C+M)
T4	Coco peat + struvite+ Mycorrhizae (C+ST+M)
T5	Soil (S)
T6	Soil+ struvite (S+ST)
T7	Soil + Mycorrhizae (S+M)
T8	Soil + struvite + Mycorrhizae(S+ST+M)
T9	Coco peat + Soil (C+S)
T10	Coco peat + Soil + struvite (C+S+ST)
T11	Coco peat + Soil + Mycorrhizae (C+S+M)
T12	Coco peat + Soil + struvite + Mycorrhizae(C+S+ST+M)

Study of plant growth parameters: The growth factors of *S. melongena* were observed after four weeks of transplantation. The height of the plant (PH) was measured from the soil surface to the tip of the uppermost leaf, and the average was calculated in centimetres. The number of leaves (NOL) was determined visually by inspecting the green leaves, whereas the stem girth (SG) was measured using a Vernier calliper and expressed in centimetres. The chosen metrics —PH, NOL, NO, SG, and yield — were selected to provide a comprehensive assessment of plant growth and development. Stem girth was included as an essential parameter because a thicker stem contributes to structural stability and improved nutrient transport, which are critical for supporting higher biomass and yield. Growth parameters were observed 30, 60, 90, and 120 days after transplantation. The yield parameters were monitored from 90 to 120 days post-transplantation until harvest, encompassing the number of flowers per plant. Fully developed fruits were harvested and weighed.

Statistical analysis: All statistical analyses were conducted using SPSS software (Version 23.0). The effects of various growing media on the various plant properties such as height of the plant, number of leaves, and stem girth of the plant were tested using a one-way ANOVA over a period of 30 to 120 days. Duncan Multiple Range Test (DMRT) at P 0.05 was used to determine the significance of differences between treatments by assigning letters of significance.

Results and discussion

Physicochemical properties of medium: While fundamental physical properties such as electrical conductivity, bulk density, and particle density showed no significant changes before and after cultivation, specific structural characteristics were altered (Table 2). The porosity of the growing medium decreased due to soil compaction, particle rearrangement, and the collapse of channels resulting from decaying roots during cultivation. These transformations did not substantially affect the basic properties of soil since they did not change the soil structure as the other physical characteristics were not affected. Simultaneously, water-holding capacity was enhanced with the cultivation, which was the result of cocopeat, mycorrhizae, and struvite. The ability of cocopeat to retain water, but not to lose it, also preserved moisture, as well as helped to improve the soil structure when it was broken down (Singh *et al.*, 2018). This was further augmented by the fact that mycorrhizae formed a large network of hyphae, cementing

Table 2. Physical properties of different plant medium before and after cultivation

Treatment	Before cultivation						After cultivation					
	EC (mS cm ⁻¹)	BD (g/cc)	PD (g/cc)	Pt (%)	WHC (%)	MC (%)	EC (mS cm ⁻¹)	BD (g/cc)	PD (g/cc)	Pt (%)	WHC (%)	MC (%)
T1	0.64	0.070	0.165	57.57	80.51	58.51	0.61	0.080	0.165	51.51	89.61	55.43
T2	1.59	0.045	0.138	67.39	79.40	69.80	1.50	0.048	0.138	65.21	85.12	66.75
T3	1.07	0.090	0.230	60.86	81.34	64.14	1.00	0.095	0.230	58.69	90.19	60.11
T4	2.05	0.068	0.254	73.22	80.90	60.12	1.79	0.077	0.254	69.68	88.91	58.78
T5	0.41	0.263	0.525	49.90	52.73	1.98	0.37	0.275	0.525	47.61	58.68	1.13
T6	0.65	0.376	0.710	47.04	49.10	5.83	0.61	0.387	0.710	45.49	54.20	4.57
T7	0.38	0.350	0.811	56.84	51.34	3.63	0.35	0.370	0.811	54.37	56.42	2.86
T8	0.53	0.398	0.895	55.53	54.45	4.89	0.50	0.410	0.895	53.93	55.75	3.24
T9	0.86	0.320	0.982	67.41	71.86	13.47	0.46	0.345	0.982	64.86	76.43	11.56
T10	1.10	0.175	0.795	77.98	68.23	11.35	1.05	0.196	0.795	75.34	72.34	9.25
T11	0.37	0.675	1.545	56.31	60.70	12.77	0.32	0.699	1.545	54.75	66.65	10.68
T12	0.98	0.460	1.115	58.74	72.53	11.87	0.93	0.480	1.115	56.69	78.58	9.98

soil particles together, and making them more porous, thereby enabling easier water retention as reported (Wahab, *et al.*, 2023). Also, there is the addition of struvite, which is a slow-release fertiliser that releases the nutrients gradually and affects the soil aggregation, which enhances the water-holding capacity of the soil further. The combination of these processes, combined with the lack of root penetration of plants, led to the reported growth of water-holding capacity following cultivation (Sharma *et al.*, 2024). Chemical analysis (Table 3) was done on pH, N, P, and K before and after cultivation. Although there was no significant difference in pH between treatments, the concentrations of N, P and K declined after cultivation. This decrease is because during growth, plants utilize these nutrients and they are eliminated along with crops harvested. Microbial activity in the soil also influences the availability of nutrients by decomposing or converting these elements to cause further depletion as is commonly reported. (Djaman, *et al.*, 2013; Yanai *et al.*, 2010).

Growth parameters: The corresponding results on Plant Height (PH), Number of Leaves (NOL), Stem Girth (SG), Number of Flowers (NOF) and Fruit Yield (FY) were statistically verified and correlated to physiochemical properties. The initial group (T1–T4) exhibited minimal growth in plant height, with a slight increase observed by 120 days. The third group (T9–

T12) exhibited better growth, reaching approximately 60 cm in height with mycorrhizae and struvite. The most considerable growth was observed in the second group (T5–T8) with the contribution of soil, struvite, and mixed media, leading to the growth. Stem girth was also on a similar pattern with T1–T4 and T9–T12 having lower girth, and T5–T8 having significant growth. This implies that the performance of struvite is similar to the traditional phosphate fertilisers.

Fig. 1. depicts that the average yield of *S. melongena*. T7 and T8 gave the highest yield with a consistent three month trend. T1–T4 (coco peat-based) showed the lowest growth whereas T9–T12 (soil and coco peat) had better results. T5–T8, which included soil, mycorrhizae and struvite, had the highest yields of 75, 82.67, 85 and 88.33 respectively. Fig. 2 shows *S. melongena* under various media. T8 (Soil + struvite + Mycorrhizae) showed the best values in all growth parameters such as height, number of leaves, stem development, flower count and yield. Yields varied significantly: T1–T4 ranged from 9.67% to 27.67%, T9–T12 from 35.67% to 57.33%, and T5–T8 from 75% to 88.33%, correlating with the complexity and balance of the growing media.

Comparing the plant parameters over a period, treatments, T5 to T8 showed the most favourable outcomes, with T8 > T7 > T6

Table 3. Chemical properties of different plant mediums before and after cultivation

Treatment	Before cultivation				After cultivation			
	pH	N mg/kg	P mg/kg	K mg/kg	pH	N mg/kg	P mg/kg	K mg/kg
T1	6.30	40.0	30.1	78.2	6.51	20.4	20.9	65.5
T2	6.41	48.2	40.7	70.5	6.63	35.5	35.3	60.2
T3	6.33	46.4	32.3	75.3	6.70	30.1	26.9	68.4
T4	6.44	50.4	45.6	69.3	6.82	43.9	38.2	55.1
T5	7.14	68.6	50.5	77.3	7.55	57.3	41.1	60.2
T6	7.40	62.3	60.2	74.2	7.67	48.1	53.9	60.6
T7	7.26	59.7	55.9	68.1	7.49	48.4	45.3	57.4
T8	7.37	60.5	58.6	75.9	7.80	52.7	49.6	63.3
T9	6.31	30.2	27.6	40.1	6.74	25.9	18.5	31.3
T10	7.66	38.2	30.1	38.9	7.60	30.6	29.2	30.9
T11	6.18	35.9	32.5	33.8	6.79	29.3	28.1	27.7
T12	7.89	40.1	30.8	37.3	8.01	31.9	24.3	30.5

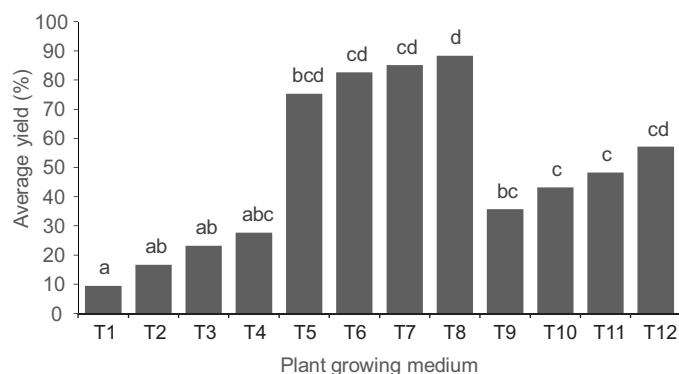


Fig. 1. The average yield of *S. melongena* in different plant medium. (T1-Cocopeat, T2-Cocopeat+Struvite, T3-Cocopeat+Mycorrhizae, T4-Cocopeat+Struvite+Mycorrhiza, T5-Soil, T6-Soil+struvite, T7-Soil+Mycorrhizae, T8-Soil+struvite+Mycorrhizae, T9-Cocopratt+Soil, T10-Cocopeat+Soil+struvite, T11-Cocopeat+Soil+Mycorrhizae, T12-Cocopeat+Soil+struvite+Mycorrhizae.)



Fig. 2. Growth *S. melongena* on twelve combinations of plant growing medium

> T5, indicating that T8 was the most effective. These results align with the reports of Uysal *et al.* (2013), wherein nutrient uptake by maize and tomato plants was observed through struvite applications. Similarly, Chopra *et al.* (2013) showed that a mix of 40% sugarcane bagasse and 60% garden soil enhanced soil fertility and *S. melongena* performance, as did an Islam *et al.* (2020) study on cocopeat with urea applications. Thus, it is clear that amendment of struvite in soil and coco peat combinations yielded 88.3%, surpassing the control group.

Effect on the growth of *S. melongena*: Results indicated a notable yield increase of approximately 200% as the plant medium transitioned from control T1 to T4, incorporating mycorrhizae and struvite into coco peat. In T5–T8, which featured diverse soil combinations, yield increased by approximately 20% compared to the control, spanning from T5 to T8. The third group, T9–T12, which combined soil and coco peat, showed a 62% higher yield in T12 compared to its control, T9, which contained only soil and coco peat. This significant difference in yield was further validated by a p -value < 0.05. These observations highlight that growth factors mainly depend on the medium.

Fig. 3 illustrates plant roots under different growth media. From the results, it is clear that the observation of higher yield in T3, T7, and T11 with the addition of mycorrhizae to the control media. Mycorrhizae form symbiotic associations with the roots of plants and fungi. These soil-dwelling microbes extensively colonize plant roots. They connect the plant with its substrate, facilitating the synthesis of growth hormones, improving nutrient absorption, and providing defence against root pathogens (Enebe and Erasmus, 2023). The yield in T3 increased by approximately 130% compared to its control, T1, while T7 showed a 13% increase relative to T5. Utilising coco peat as the sole growing medium provides limited nutrients, resulting in lower fertility compared to soil-based mediums. However, the addition of mycorrhizae enhances yield factors, as evidenced by the observed results. Particularly, phosphorus (P) content in the treatment using biofertilizer rose to 32 mg/kg and in the combined treatment using struvite it rose further to 45.6mg/kg. In addition, the uptake of nutrients was significantly greater in the coco peat medium, resulting in a significant increase of 130 percent in yield as compared to moderate fertile soils where the increase was only 15 percent. It has been reported that mycorrhizal fungi enhance nutrient uptake by synthesizing enzymes to break non-soluble nutrients into bioavailable soluble forms that are directly transported to the plant root system (Huey *et al.*, 2020)

Also, mycorrhizae form vesicles on root hairs to store nutrients,

which is crucial in increasing the area of soil contact of plants and making them able to reach a broader spectrum of nutrients and water. Research has shown that AMF improves the growth of peach seedlings in potted environment, where the concentration of essential elements, including K, Mg, Fe, and Zn in leaves and roots, and Ca in leaves and Cu and Mn in roots, improved significantly (Bhantana *et al.*, 2021). Jajoo and Mathur (2021) note that enriching plant roots with mycorrhizal fungi improves the productivity of plants by effectively taking advantage of the soil micro- and macronutrients and water. Although the research on struvite amendment is very extensive, there is a lack of research incorporating the use of mycorrhizae. The encouraging results about the improvement of the available phosphorus and the growth factors in the soilless medium demonstrate the advantages of integrated fertilizer management.

Effect of struvite on *S. melongena* growth: The effects of application of struvite on growth of the plant were investigated through the analysis and comparison of the growth parameters and average yield of the plants in the various treatment plots. The T2, T6, and T10 growing media are made of struvite and soil or coco peat. The *S. melongena* in of these plots had a higher yield than the corresponding controls in the set, i.e. T1, T5 and T9. These findings are comparable to those that Jama-Rodzenska *et al.* (2023) and Gell *et al.* (2011) found. Although addition of struvite led to increased yields in all combinations, it was quite interesting to note that the increase in yield was the greatest in the first set, T1-T2, which was at 60%. This is explained by the fact that nutrient content of coco peat is lower than in soil, and the effect of struvite is more significant. Besides, the presence of struvite and mycorrhizae as observed in T4, T8 and T12 enhanced the growth of the plants with the highest yield of 88% in T8. This is explained by increased availability of nutrients to roots. The mycorrhizal fungal sheath serves as a nutrient storage, which guarantees the plant host a steady supply of nutrients even in cases when nutrient concentrations in the soil are low (Nafady *et al.*, 2019).

Correlation between soil and plant growth properties: Table 4 shows the correlation of soil properties. WHC and MC have significant correlations with EC, BD, Pt and pH. It is worth noting that pH, K and P show a negative correlation whereas WHC and Pt show a positive correlation. N, P and MC have a high correlation with BD and MC. WHC and MC show higher relative correlations with pH, EC, BD, Pt and WHC. The

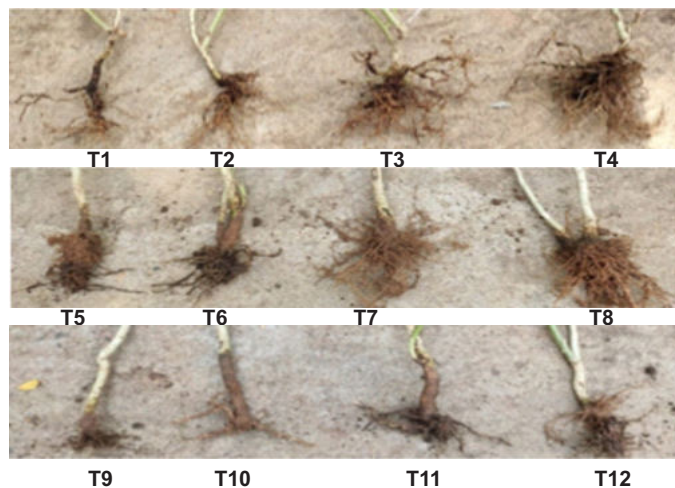


Fig. 3. Growth of roots in different plant media

correlation between PD and EC displays the least strength. These findings can serve as indicators for monitoring the quality of soil and coco peat when treated with struvite. The significance of correlation is established at the 0.05 level (95% confidence) and the 0.01 level (99% confidence). Further analyses, such as factor analysis, are necessary to identify the key parameters influencing soil and coco peat, thereby avoiding redundancy.

Table 4. Correlation between soil properties

Variables	EC	N	P	K	BD	PD	Pt	WHC	MC
H	-0.26	0.30	0.32	-0.21	0.33	0.33	-0.29	-0.62**	-0.68**
EC	1.00	-0.12	-0.12	0.09	-0.64**	-0.42*	0.74**	0.69**	0.70*
N		1.00	0.91**	0.63**	-0.05	-0.14	-0.40	-0.50*	-0.29
P			1.00	0.59	0.12	-0.11	-0.49*	-0.61**	-0.03
K				1.00	-0.51*	-0.70**	-0.27	0.02	0.38
BD					1.00	0.90**	-0.46*	-0.59*	-0.75**
PD						1.00	-0.07	-0.33	-0.66**
Pt							1.00	0.76**	0.51*
WHC								1.00	0.83**
MC									1.00

*The correlation is statistically significant at the 0.05 level with a two-tailed test. **The correlation is statistically significant at the 0.01 level with a two-tailed test.

Table 5 displays the correlation analysis between soil properties and plant growth parameters. WHC, EC and MC exhibit a negative correlation with PH, NOL, SG, NOF, and FY, which aligns most closely with the data. Similarly, BD exhibits the strongest correlation with pH and positive correlations with other factors. N shows consistent positive correlations with other variables. FY exhibits steady growth with a consistent correlation along with N, PD, and P. The significance of correlation is established at the 0.05 level (for 95%) and the 0.01 level (for 99%).

One-way ANOVA test results showed significant differences in plant height, number of leaves and stem girth (Table 6). The obtained *p*-values < 0.05 for all plant growth parameters confirmed that there are statistically significant differences among them at 30, 60, 90, and 120 days. The mean comparison of different treatments indicates a significant difference in the number of flowers and yield at different time points (Table 7). Specifically, T4 showed a significant difference compared to its control (T1), as well as T8 and the control, T5. Among the treatments, T8 exhibited the maximum number of flowers at 90 days (9.67) and at 120 days (12.00). The maximum yield was observed at 120 days in T8 (88.33%), followed by T7 (85.11%). The lowest yield of 9.41 was obtained from the T1 treatment, which served as unamended

Table 6. Mean comparison of plant height, number of leaves and stem girth in different plant mediums

Treatment	Days	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
PH	30	9.00g	12.67fg	14.33fg	13.33fg	22.70cd	24.00bc	30.00ab	32.33a	15.33fg	14.67fg	17.33ef	20.67de
	60	37.90d	39.19d	39.53d	41.69c	47.89b	48.36b	45.87bc	54.55a	47.26b	41.43c	42.91c	44.32bc
	90	24.67f	25.43f	34.00e	37.40e	51.00c	52.70c	61.33b	71.33a	39.20d	41.13d	45.00d	49.67c
	120	37.00g	37.55g	41.00f	43.00f	57.17d	64.37c	75.00b	85.67a	50.60e	52.17e	55.57d	59.67d
NOL	30	4.67j	6.67ij	8.00hi	10.00gh	21.33cd	22.33bc	25.33ab	27.67a	12.00fg	14.00fg	17.00ef	19.00de
	60	16.95c	17.43c	17.81c	18.45c	20.97ab	21.39ab	20.45abc	22.76a	19.85bc	17.89c	19.61bc	19.73bc
	90	14.67e	16.67e	18.00de	20.00de	28.00bc	32.00ab	32.33ab	35.33a	22.67cd	23.67cd	27.33bc	28.00bc
	120	20.00e	21.33e	24.00e	27.00d	34.00bc	35.67abc	38.00ab	41.00a	29.00cd	30.00cd	32.67bc	33.00bc
SG	30	0.77h	1.87gh	2.43fg	2.80ef	5.30c	7.17b	8.45a	8.50a	2.93ef	3.83de	3.83de	4.87cd
	60	1.73c	1.77c	1.79c	1.88c	2.07b	2.09b	2.04b	2.23a	2.00b	1.85c	1.95bc	1.95bc
	90	1.90h	3.03g	3.33g	4.00f	8.83c	9.07c	10.00b	10.70a	4.93e	5.07e	6.20e	7.60d
	120	3.02i	3.73h	4.13h	5.43g	9.17d	10.40c	11.17b	12.37a	6.20f	6.63f	7.10f	8.67e

Means within a column followed by the same letter are not significantly different at *P* < 0.05 according to Duncan's Multiple Range Test (DMRT). PH-Plant Height, NOL-Number of Leaves, SG-Stem Girth.

Table 5. Correlation between plant growth parameters and soil properties

Parameter	PH	NOL	SG	NOF	FY
pH	0.607*	0.634*	0.610*	0.614*	0.582*
EC	-0.635*	-0.621*	-0.625*	-0.660*	-0.684*
N	0.559	0.681*	0.632*	0.634*	0.655*
P	0.627*	0.661*	0.581*	0.615*	-0.642*
K	-0.094	-0.052	-0.117	-0.116	-0.076
BD	0.723**	0.704*	0.676*	0.691*	0.700*
PD	0.635*	0.581*	0.589*	0.601*	0.585*
Pt	-0.526	-0.612*	-0.530	-0.545	-0.608*
WHC	-0.879**	-0.910**	-0.865**	-0.922**	-0.952**
MC	-0.815**	-0.822**	-0.842**	-0.866**	-0.849**

*The correlation is statistically significant at the 0.05 level with a two-tailed test. **The correlation is statistically significant at the 0.01 level with a two-tailed test. PH-Plant Height, NOL-Number of Leaves, SG-Stem Girth, NOF-Number of Flower, FY- Fruit Yield

cocopeat control. Statistical analysis has proven that integrated fertiliser management offers better agricultural practices than traditional farming methods.

We hypothesised that struvite would be as effective as other phosphate fertilisers under controlled conditions. Our results confirmed this, showing a significant difference in P uptake between cocopeat, soil, and the control (Fig. 2). struvite performed better in soil than in cocopeat due to limited nutrients in cocopeat. Adding AMF to struvite (T4) improved agronomic efficiency, resulting in higher yields and P uptake compared to traditional soil (T8). AMF enhanced P acquisition by making soil P more accessible to plant roots. We expected AMF to boost struvite dissolution and effectiveness as a slow-release fertilizer. This was confirmed, especially in P-limited conditions, where AMF collaboration increased P uptake by about 130%. This aligns with findings by Di Tomassi *et al.* (2021), who reported similar effects of AMF and organic acids on struvite surface weathering. AMF also increased biomass and nutrient uptake in tomatoes fertilized with struvite compared to monoammonium phosphate (Thiessen Martens, 2022), in which P uptake depended on effective scavenging rather than additional dissolution. Similarly, Schwalb *et al.* (2021) noted that uninoculated cereal rye absorbed more phosphorus (P) from struvite due to its greater root biomass.

These findings highlight that plant P uptake, whether with or without AMF, depends on both the plant and soil types. Other AMF benefits, like improved water and nutrient supply, stress

Table 7. Mean comparison of number of flower and yield in different plant mediums

Treatment	Flower (90 days mean)	Flower (120 days Mean)	Yield (120 days Mean)
T1	1.34 a	2.45 a	9.41 a
T2	2.33 ab	4.67 ab	16.67 ab
T3	4.67 ab	6.00 ab	23.21 ab
T4	5.00 abc	7.10 abc	27.67 abc
T5	7.00 bcd	8.48 bcd	75.33 bcd
T6	8.00 cd	10.44 cd	82.67 cd
T7	9.10 cd	11.33 cd	85.11 cd
T8	9.67 d	12.00d	88.33 d
T9	5.33 bc	8.20 bc	35.67 bc
T10	7.00 c	8.33 c	43.22 c
T11	8.22 c	9.00 c	48.32 c
T12	8.60 cd	10.10 cd	57.11 cd

Means within each column followed by the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level.

tolerance, and soil quality, also matter. Our study showed that cocopeat treated with struvite, mycorrhizae, or a combination of both had significantly better growth than untreated cocopeat. In cocopeat, the P bioavailability is almost negligible, therefore, P fertilizers are often applied at a level higher than the requirements. The impact of slow and delayed struvite release can be mitigated with the implementation of combined treatment. This suggests struvite can improve low-phosphorus plant media. Additionally, the combination of cocopeat and soil is important, although it has not been widely studied. Therefore, this study aimed to answer the question often asked: what kind and how much fertiliser is appropriate to favour AMF establishment and function. The results of the study pointed to the higher compatibility of the struvite and AMF in the soilless mixes, which were most effective in terms of growth enhancement caused by AFM. Moreover, the increasing media enriched with cocopeat can also retain more nutrients in the form of nutrients that can be taken by plants because of the improved capacity of roots to take in nutrients that is facilitated by AMF colonisation. This observation is in agreement with the reports of potato production in soilless media with the use of arbuscular mycorrhizal fungi (AMF). Use of struvite caused significant influence on vegetative growth of *S. melongena*. The effect was reflected in more number of leaves, tallness of the plant and a thicker stem compared to the control. Mycorrhizae in combination with soil/cocopeat amendment, which was reported first in this study, positively influenced growth and yield. This blend may have the advantage of the early uptake of phosphorus by mycorrhizae as well as the constant release of phosphorus by struvite with time. Additionally, sourcing phosphorus from alternative secondary materials would simultaneously support a circular economy. Further studies on the immobilization efficiency and mobility of phosphorus by biofertilizers are needed, as they will help conserve phosphorus consumption through struvite crop rotation and alleviate future pressure on the finite source of mineral phosphate.

The scope of these findings may be further revealed by future studies in field experiments using different soils, as well as

soilless mixes, to determine the relationship under more realistic conditions for sustainable crop management practices.

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References

- Awang, Y., A.S. Shaharom, R.B. Mohamad and A. Selamat, 2009. Chemical and physical characteristics of cocopeat-based media mixtures and their effects on the growth and development of *Celosia cristata*. *Am. J. Agric. Biol. Sci.*, 4(1): 63-71.
- Bhantana, P., M.S. Rana, X.C. Sun, M.G. Moussa, M.H. Saleem, M. Syaifudin and C.X. Hu, 2021. Arbuscular mycorrhizal fungi and its major role in plant growth, zinc nutrition, phosphorus regulation and phytoremediation. *Symbiosis*, 84: 19-37.
- Bhatt, P., S. Singh and P.K. Pant, 2022. Validation of soil test based fertilizer prescription model for optimizing the use of chemical fertilizer, improved performance of brinjal (*Solanum melongena* L.) and soil biological properties in Subtropical Mollisols. *Commun. Soil Sci. Plant Anal.*, 54(3): 332-344.
- Bindraban, P.S., C.O. Dimkpa and R. Pandey, 2020. Exploring phosphorus fertilizers and fertilization strategies for improved human and environmental health. *Biol. Fertil. Soils*, 56(3): 299-317.
- Chopra, A.K., S. Srivastava, V. Kumar and C. Pathak, 2013. Agropotentiality of distillery effluent on soil and agronomical characteristics of *Abelmoschus esculentus* L. (okra). *Environ. Monit. Assess.*, 185: 6635-6644.
- Daneshgar, S., A. Callegari, A.G. Capodaglio and D. Vaccari, 2018. The potential phosphorus crisis: resource conservation and possible escape technologies: a review. *Resour.*, 7(2): 37.
- Di Tomassi, I., N. Chatterjee and F.H. Barrios-Masias, 2021. Arbuscular mycorrhizae increase biomass and nutrient uptake of tomato fertilized with struvite compared to monoammonium phosphate. *Plant Soil*, 464: 321-333.
- Djaman, K., S. Irmak, D.L. Martin, R.B. Ferguson and M.L. Bernards, 2013. Plant nutrient uptake and soil nutrient dynamics under full and limited irrigation and rainfed maize production. *Agron. J.*, 105(2): 527-538.
- Enebe, M.C. and M. Erasmus, 2023. Symbiosis - A perspective on the effects of host traits and environmental parameters in arbuscular mycorrhizal fungal richness, colonization and ecological functions. *Agric.*, 13(10): 1899.
- Ferron, L.M.E., J.W. Van Groenigen, G.F. Koopmans and A. Vidal, 2025. Can earthworms and root traits improve plant struvite-P uptake? A field mesocosm study. *Agric. Ecosyst. Environ.*, 377: 109255.
- Gell, K., F.J. De Ruijter, P. Kuntke, M. De Graaf and A.L. Smit, 2011. Safety and effectiveness of struvite from black water and urine as a phosphorus fertilizer. *J. Agric. Sci.*, 3(3): 67.
- Hernández Jiménez, J.E., J. Nyiraneza, T.D. Fraser, H.C.P. Brown, I.J. Lopez-Sanchez and L.R. Botero-Botero, 2020. Enhancing phosphorus release from struvite with biostimulants. *Can. J. Soil Sci.*, 101(1): 22-32.
- Huey, C.J., S.C. Gopinath, M.N.A. Uda, H.I. Zulhaimi, M.N. Jaafar, F.H. Kasim and A.R.W. Yaakub, 2020. Mycorrhiza: a natural resource assists plant growth under varied soil conditions. *3 Biotech*, 10: 1-9.
- Islam, M.S., B. Hossain, I.J. Keya and M.M. Islam, 2020. Appraisal of different doses of nitrogen fertilizer on growth and yield of eggplant (*Solanum melongena* L.). *Arch. Agric. Environ. Sci.*, 5(4):452-456.

- Jajoo, A. and S. Mathur, 2021. Role of arbuscular mycorrhizal fungi as an underground saviour for protecting plants from abiotic stresses. *Physiol. Mol. Biol. Plants*, 27(11): 2589-2603.
- Jama-Rodzeńska, A., B. Gałka, A. Szuba-Trznadel, A. Jandy and J.A. Kamińska, 2023. Effect of struvite (Crystal Green) fertilization on soil element content determined by different methods under soybean cultivation. *Sci. Rep.*, 13(1): 12702.
- Kalaivani, K. and M. Jawaharlal, 2019. Study on physical characterization of cocopeat with different proportions of organic amendments for soilless cultivation. *J. Pharmacogn. Phytochem.*, 8(3): 2283-2286.
- Kavatagi, P.K. and H.C. Lakshman, 2014. Effect of arbuscular mycorrhizal fungi, pressmud and growth regulator on *Solanum lycopersicum* L. *Int. J. Pure Appl. Sci. Technol.*, 21(2): 11.
- Khan, M.Z., M.D. Era, M.A. Islam, R. Khatun, A. Begum and S.M. Billah, 2019. Effect of coconut peat on the growth and yield response of *Ipomoea aquatica*. *Am. J. Plant Sci.*, 10(3): 369.
- Liu, W., Y. Zhang, S. Jiang, Y. Deng, P. Christie, P.J. Murray, X. Li and J. Zhang, 2016. Arbuscular mycorrhizal fungi in soil and roots respond differently to phosphorus inputs in an intensively managed calcareous agricultural soil. *Sci. Rep.*, 6: 24902.
- Nafady, N.A., M. Hashem, E.A. Hassan, H.A. Ahmed and S.A. Alamri, 2019. The combined effect of arbuscular mycorrhizae and plant-growth-promoting yeast improves sunflower defense against *Macrophomina phaseolina* diseases. *Biol. Control*, 138: 104049.
- Ossai, C., 2021. Poultry manure and arbuscular mycorrhiza fungi remediation of sodium chloride induced substrate salinity for pepper production. *J. Curr. Opin. Crop Sci.*, 2(3): 363-368.
- Rahman, M.M., M.A.M. Salleh, U. Rashid, A. Ahsan, M.M. Hossain and C.S. Ra, 2014. Production of slow release crystal fertilizer from wastewaters through struvite crystallization - A review. *Arab. J. Chem.*, 7(1): 139-155.
- Schwalb, S.A., M. Hemkemeyer, C. Watson and F. Wichern, 2021. Mycorrhiza reduces phosphorus uptake from struvite in rye (*Secale cereale* L.) plants. *J. Soil Sci. Plant Nutr.*, 21: 3451-3460.
- Shaddel, S., H. Bakhtiary-Davijany, C. Kabbe, F. Dadgar and S.W. Østerhus, 2019. Sustainable sewage sludge management: From current practices to emerging nutrient recovery technologies. *Sustain.*, 11(12): 3435.
- Sharma, M., J. Pang, B.S. Mickan, M.H. Ryan, S.N. Jenkins and K.H. Siddique, 2024. Wastewater-derived struvite has the potential to substitute for soluble phosphorus fertiliser for growth of chickpea and wheat. *J. Soil Sci. Plant Nutr.*, 24: 3011-3025.
- Singh, M.C., D.S. Kachwaya and K. Kalsi, 2018. Soilless cucumber cultivation under protective structures in relation to irrigation coupled fertigation management, economic viability and potential benefits: a review. *Int. J. Curr. Microbiol. Appl. Sci.*, 7(3): 2451-2468.
- Thiessen Martens, J.R., 2022. Characterizing the behaviour and efficacy of struvite fertilizer for organically managed crops in Manitoba soils. (Ph.D. thesis) Univ. Manitoba, Winnipeg, Manitoba.
- Uysal, A., S. Demir, E. Sayilgan, F. Eraslan and Z. Kucukyumuk, 2013. Optimization of struvite fertilizer formation from baker's yeast wastewater: growth and nutrition of maize and tomato plants. *Environ. Sci. Pollut. Res.*, 21: 3264-3274.
- Wahab, A., M. Muhammad, A. Munir, G. Abdi, W. Zaman, A. Ayaz and S.P.P. Reddy, 2023. Role of arbuscular mycorrhizal fungi in regulating growth, enhancing productivity and potentially influencing ecosystems under abiotic and biotic stresses. *Plants*, 12(17): 3102.
- Wen, Z., H. Li, Q. Shen, X. Tang, C. Xiong, H. Li, J. Pang, M.H. Ryan, H. Lambers and J. Shen, 2019. Trade-offs among root morphology, exudation and mycorrhizal symbioses for phosphorus-acquisition strategies of 16 crop species. *New Phytol.*, 223(2): 882-895.
- Yanai, J., S. Nakata, S. Funakawa, E. Nawata, R. Katawatin and T. Kosaki, 2010. Effect of NPK application on growth, yield and nutrient uptake by sugarcane on a sandy soil in Northeast Thailand. *Trop. Agric. Dev.*, 54(4): 113-118.

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