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The Impact of Struvite and Soil pH on Chilli Pepper Plant Growth and Nutrient Release

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Struvite ($MgNH_4PO_4{\cdot}6H_2O$), a sustainable and highly efficient slow-release fertiliser, is gaining significant attention as a promising solution for nutrient recovery from waste streams. Its unique composition, which includes essential nutrients like nitrogen (N) and phosphate (PO_4), makes it an effective alternative to conventional fertilisers. In contrast, the widespread application of traditional NPK fertilisers often leads to a high loss of nutrients in the soil through leaching and runoff, negatively impacting both plant growth and overall soil health. While struvite has shown high efficacy in cultivating various crops, its specific effectiveness for growing chili pepper plants and its nutrient leaching behaviour in tropical soil environments have not been extensively studied. To address this knowledge gap, a comprehensive 60-day pot trial was conducted, comparing struvite with conventional NPK fertiliser. The experiment used twelve pots with different soil pH levels, treating them with three fertiliser types at two different dosages, along with a control group. The study, conducted outdoors under shade, revealed that struvite applied at a higher dosage in alkaline soil (pH up to 8.5±0.05) significantly enhanced plant growth compared to NPK treatments, achieving a maximum plant height of 33.4±2.0 cm, a plant body weight of 23.6±2.1 g, and a high leaf count of 57±3.0 leaves. While NPK fertilisers also performed better in alkaline soils, they did not match struvite's performance. Critically, the study confirmed that struvite provides a more controlled and gradual nutrient release than NPK. For instance, the highest PO_4 release rate for struvite was 510±10.0 mg/L on day 25 under acidic conditions, while in alkaline soils, its release was slower and more sustained, peaking at approximately 250-290±5.0 mg/L. These findings highlight the potential of struvite as a viable and sustainable alternative to conventional fertilisers, contributing to reduced nutrient runoff, supporting circular economy practices, and ultimately improving long-term soil health.

Keywords: struvite; nitrate; phosphate; NPK fertiliser; chili pepper

I. INTRODUCTION

The agricultural sector faces the dual challenge of increasing food production while ensuring environmental sustainability and resource efficiency (Mansour *et al.*, 2024). Fertilisers play a vital role in enhancing crop growth; however, their excessive and prolonged use poses significant ecological and health risks. Conventional fertilisers, such as NPK and diammonium phosphate, contribute to nutrient accumulation in soils, leading to groundwater and surface water contamination through leaching and runoff. Phosphorus runoff accelerates eutrophication and algal blooms, while nitrogen compounds convert into harmful nitrates, threatening drinking water quality (Kent *et al.*,

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2024). To promote sustainable agricultural practices, it is essential to assess the nutrient release rates of fertilisers, ensuring their efficiency while minimising environmental impact.

Struvite ($MgNH_4PO_4.6H_2O$), a slow-release fertiliser, has gained high attention as an eco-friendly fertiliser; its low solubility and slow-release properties offer a balanced nutrients source for plants and mitigate adverse environmental impacts (Li *et al.*, 2019; Nageshwari & Balasubramanian, 2022). This contrasts with conventional fertilisers, such as NPK and monoammonium phosphate, that have high solubility, leading to rapid nutrient release and potential leaching (Hariyadi *et al.*, 2019). The controlled nutrient release from struvite minimises nutrient losses and decreases the risk of groundwater contamination (Rahman *et al.* 2014). Conventional NPK fertilisers, while effective, can contribute to nutrient leaching, groundwater pollution, and eutrophication (Karmakar & Kashyap, 2021). Struvite has been successfully produced from different types of waste streams such as landfill leachate (de Teves Inácio *et al.*, 2022; Lucero-Sobarzo *et al.*, 2022; Warmadewanthi *et al.*, 2021), human urine (Sathiasivan *et al.*, 2019; Seodigeng *et al.*, 2021) and anaerobic digestate (Galamini *et al.*, 2023; Lorick *et al.*, 2020), making it a promising solution for nutrients' recovery. Furthermore, struvite has demonstrated a high potential in enhancing the yield of different crops (Di Tomassi *et al.*, 2021; Kontárová *et al.*, 2022; MacDonnell *et al.*, 2022; Rahman *et al.*, 2014; Ryu *et al.*, 2012; Valle *et al.*, 2022), which makes it a sustainable option for fertilisers' application. Nevertheless, fertilisation is a common source of nitrates (NO_3) released to the soil, hence reaching groundwater through percolation (Zhao *et al.*, 2011) and water bodies via runoff (Wang *et al.*, 2013), which negatively affects drinking water quality. Therefore, it is of a paramount importance to investigate the nitrates (NO_3) leaching behaviour from struvite to evaluate struvite's applicability in the agronomic field.

The leaching of nutrients from struvite fertiliser has been studied across various crops cultivated in different soil types. Pérez-Piqueres *et al.* (2023) studied the fertilisation efficiency of struvite for planting tall fescue in different types of Mediterranean soils. They found that approximately 20% of the N released from struvite was not utilised by plants, indicating a relatively efficient nitrogen uptake. Several studies applied struvite fertiliser in the agronomic field, such as valerian, dill, coriander, tomato, parsley, basil, rocket and cress (Yetilmezsoy *et al.*, 2020), rice and wheat (Wang *et al.*, 2023a), Chinese cabbage and cucumber (Min *et al.*, 2019), maize and soybean (Hertzberger *et al.*, 2021) and flax and alfalfa grass (Thiessen Martens *et al.*, 2022). However, most of these studies focused on the fertigation effect of struvite as a P fertiliser, not as a N supply, which limits the explored information about NO_3 release rates and behaviour.

Leaching of N and P from struvite has been studied in different forms. Simms *et al.* (2024) and Anderson *et al.* (2021) compared the leaching properties of electrochemically precipitated struvite to conventional P fertilisers in various soil types. In both studies, the authors found that nutrients' leaching variations were mainly due to the differences in soil pH and texture. Several factors affect leaching rates of N and P from struvite, most importantly soil pH (Degryse *et al.*, 2017) and struvite characteristics. To the best of our knowledge, limited research has explored the effectiveness of struvite in cultivating chili pepper plants in tropical soils with varying pH conditions. This study examines the leaching behaviour of N and P from chemically precipitated struvite under different tropical soil conditions, highlighting its potential as a sustainable fertiliser for reducing nutrient loss and minimising environmental impact.

II. MATERIALS AND METHOD

A. Struvite Production

Struvite fertiliser was chemically precipitated in synthetic solution. Equation (1) expresses the general reaction of struvite formation:

$$Mg^{2+} + NH_4{}^{+} + PO_4{}^{2-} + 6H_2O \rightarrow MgNH_4PO_4.6H_2O \quad (1)$$

To conduct chemical precipitation of struvite, magnesium chloride ($MgCl_2$) and sodium dihydrogen phosphate (NaH_2PO_4) were applied as Mg and P sources, respectively, in 1 L of synthetic solution. The molar ratio of Mg:N:P was maintained at 1.5:1:1.5 and pH was adjusted at 8.50±0.05, just after the mixing of Mg and P salts, using sodium hydroxide (NaOH) solution. After that, the sample was stirred at a speed of 120 rpm for 30 min using a magnetic stirrer, then left to settle down for 1 hour. Finally, struvite was filtered using glass fibre filter papers (Whatman, pore size = 0.45 µm), washed with deionised water and dried at room temperature. The procedure was repeated to obtain as much struvite as needed.

B. Pot Trial Experiment

The pot trial experiment was conducted outdoors in a shaded area using horticultural plastic pots, each containing 2 kg of homogeneous loamy soil originated from a farming area at Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia. The soil was collected from the topsoil layer (0-20 cm), air dried, sieved (<2 mm), and thoroughly mixed before potting. Plants were exposed to natural daylight without supplementary lighting, with ambient temperatures ranging from 24 to 26 °C. Each pot was irrigated daily with 250 mL of tap water, and leachate samples were collected at 3-day intervals for nutrient analysis. All experimental conditions were applied uniformly across treatments to ensure consistency. Two sets of pots were applied: Set 1 used the original soil, which was acidic (pH 5.90±0.05), while for Set 2 the soil pH was adjusted to be alkaline (pH 7.40±0.05), using calcium carbonate ($CaCO_3$) and treatment was duplicated. As illustrated in Figure 1, each treatment comprised a total of 10 pots with varying soil pH conditions.

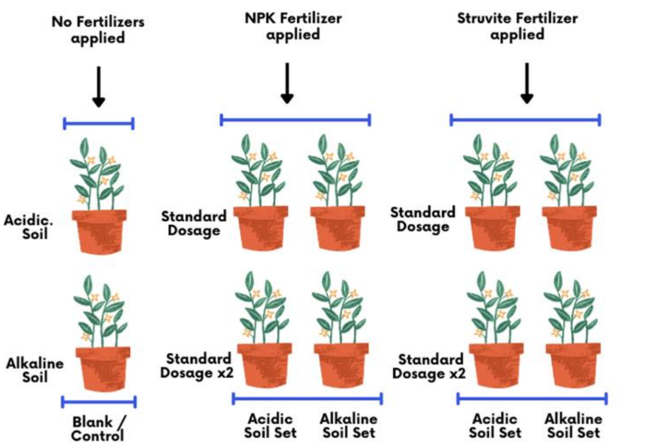


Figure 1. Pot trial experiment layout per treatment

In general, the required amount of $CaCO_3$ is influenced by soil texture, organic matter content, and plant type. For instance, soils with low clay content require less lime than those with high clay content to achieve the same pH adjustment. Through a preliminary experiment (data not shown), it was found that approximately 3.262 g/pot were required to increase soil pH by 1.0. Subsequently, to achieve an alkaline soil (pH 8-8.5), 5.219 g of $CaCO_3$ were added to the pots designated for the alkaline soil sets. In each pot, five chili pepper seeds were sown, and the seedlings (21 days old) were thinned to one plant per pot. Two distinct types of fertilisers were applied in two different doses, along with a control group that received no fertiliser. A standard fertiliser dosage was used, based on scientific recommendations by Min *et al.* (2019), who considered the standard dosage for chili pepper to be 2.9 g/pot. In the current study, both standard and increased dosages were applied for each set, with the increased dosage set at 5.7 g/pot, i.e. nearly double the standard dosage.

C. Analytical Methods

Plant growth was assessed using plant height (measured from the soil surface to the apical meristem using a ruler) and number of fully expanded leaves per plant. As chili pepper plants typically complete their active vegetative growth phase within 8-9 weeks (Souri & Sooraki, 2019), the dry weight of each plant was measured after 60 days. The dry weight was measured by harvesting the above-ground plant parts, oven-drying them at 65 °C for 72 hours until a constant weight was achieved and weighing the dried samples using an analytical balance. Leachate samples were collected at 3-day intervals and analysed for NO_3 and PO_4 using colorimetric spectrophotometric methods with commercially available reagents (NitraVer® and PhosVer®) and analysed using a UV–Vis spectrophotometer (DR6000, Hach).

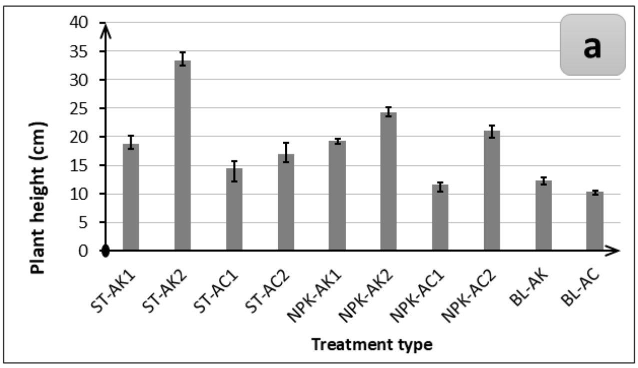
All experimental data were statistically analysed to evaluate the effects of fertiliser type, application rate, and soil pH on chili pepper growth and nutrient release behaviour. Each treatment was performed in triplicate, and one-way analysis of variance (ANOVA) was applied to assess significant differences among treatments for plant growth parameters, including plant height and number of leaves per plant. Statistical significance was determined based on F-values and P-values, with a significance level set at $P<0.05$.

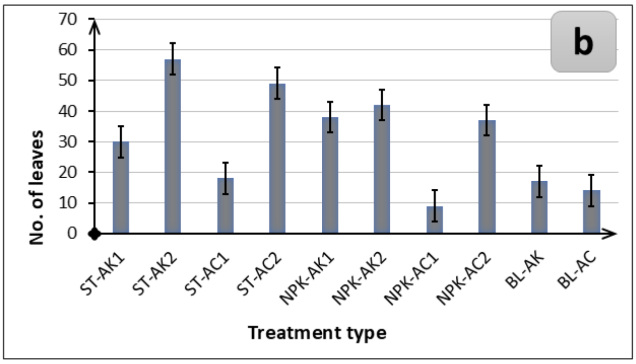
Similarly, one-way ANOVA was used to compare PO and NO release rates among struvite and NPK fertilisers treatments under acidic and alkaline soil conditions. Where applicable, unpaired t-tests were conducted to compare nutrient release performance between struvite and NPK fertilisers at equivalent application rates and soil pH conditions. Results were interpreted using a significance threshold of $P<0.05$, while P-values above this level were considered not statistically significant. Statistical outputs, including degrees of freedom, sum of squares, mean squares, F-values, and P-values, are reported in the corresponding tables.

III. RESULT AND DISCUSSION

A. Cultivation of Chili Pepper

The study investigated struvite's potential as a fertiliser, with comparisons made to NPK fertiliser and a control group. The composition of the laboratory-produced struvite was 11.28% Mg, 5.43% N, and 11.32% P, which is comparable to the theoretical composition of pure struvite (9.9% Mg, 5.7% N, and 12.6% P) as reported by Doyle & Parsons (2002). Measurements of plant height and leaf count were taken regularly. On the 60^{th} day of the experiment, plant dry weight was assessed, offering insight into the effects of different cultivation conditions on chili growth. A comparative analysis of plant growth under different treatments is presented in Figure 2, considering plant height, number of leaves and plant dry weight. The maximum plant height of 33.4±2.0 cm was achieved by the Struvite – Alkaline (II) treatment, as shown in Figure 2(a), indicating its superior effectiveness in promoting growth. Conversely, the minimum plant height of 10.3±0.5 cm after 60 days was observed in the Blank-Acidic treatment.





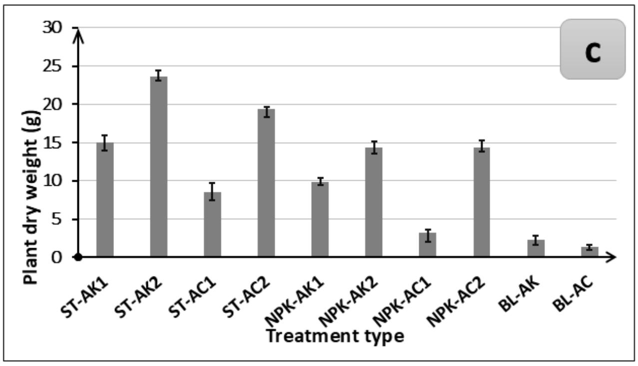


Figure 2. Plants growth results under different soil conditions; (a) plant height, (b) number of leaves, (c) plant dry weight. (ST: Struvite fertiliser; NPK: NPK fertiliser; AK1: Alkaline standard dosage; AK2: Alkaline doubled dosage; AC1: Acidic standard dosage; AC2: Acidic doubled dosage; BL-AK: Blank alkaline soil; BL-AC: Blank acidic soil)

An interesting pattern in the comparative effectiveness of NPK treatments in different soil types is revealed by Figure 2(a). Greater plant height was observed with NPK-Alkaline treatments compared to those in acidic soils, suggesting a more conducive environment for chili pepper growth in alkaline soils. The importance of soil pH in determining treatment effectiveness is highlighted, but it should be noted that optimal pH levels can vary among chili varieties. For example, some thrive in acidic soil with a pH between 5.5 and 6.5, while others can tolerate a broader pH range, from 6.8 to 7.0 (Souri & Sooraki, 2019).

Superior outcomes in terms of leaf count per plant were observed under different struvite treatments, as shown in Figure 2(b). The Struvite-Alkaline (II) treatment produced the highest leaf count (57±3.0), followed by Struvite-Acidic (II) and NPK-Alkaline (II) with 49±2.0 and 42±2.0 leaves, respectively. Despite an increase in leaf count with dosage, the Struvite-Acidic (I) treatment underperformed. A noticeable difference in chili pepper growth patterns among fertiliser type was evident. More robust growth was recorded for chili peppers treated with Struvite-Alkaline (II) compared with those treated with NPK-Alkaline (II). This is probably due to the slow and sustained nutrient release characteristics of struvite and its favourable interaction with alkaline soil conditions; as a slow-release fertiliser, struvite provides P and other nutrients gradually over time, more closely matching plant demand and reducing nutrient fixation compared with highly soluble forms found in NPK fertilisers, which are more prone to rapid immobilisation in soil and less efficient nutrient uptake later in the growing season (Degryse *et al.*, 2017; Massey *et al.*, 2009; Thiessen Martens *et al.*, 2022). A comparable trend was reported by a two-year field study conducted by Wang *et al.* (2023a) in East China. Even with a constant P application rate, the authors found that the struvite treatment resulted in slightly higher yield and aboveground biomass compared to the conventional fertilisation method. In the current study, despite NPK-Alkaline (II) being the second-best treatment in terms of plant height, its performance was closely aligned with that of the Struvite-Acidic (II) treatment regarding the number of leaves per plant. This finding is consistent with several previous studies. Erdal *et al.* (2024) reported that the application of struvite recovered from biogas liquid digestate significantly enhanced lettuce growth, resulting in higher fresh and dry biomass compared with conventional commercial fertilisers (NPK, monoammonium phosphate, di-ammonium phosphate, and triple superphosphate). Uysal *et al.* (2014) evaluated the fertilisation efficiency of struvite recovered from baker's yeast effluents. They reported that tomato plants fertilised with struvite produced greater dry biomass than those treated with NPK fertiliser, whereas a double dose of struvite was required to achieve higher efficiency than NPK in maize cultivation. Collectively, these findings and the current results reinforce the potential of struvite as a sustainable nutrient source in agricultural production.

Moreover, Figure 2(a) and (c) illustrate a clear positive relationship between fertiliser application rate and plant growth performance. This trend is evident in the measurements of plant height and dry weight, where plants grown under the Struvite-Alkaline (II) treatment exhibited nearly double the height and weight compared to those under Struvite-Alkaline (I) treatment. According to Pérez-Piqueres *et al.* (2023), plants supplied with higher dose of struvite exhibited enhanced vegetative growth, with up to 25-30% greater plant height and leaf number compared to the control treatment. This confirms that higher struvite application rate promotes stronger crop growth and canopy development.

Table 1 shows the ANOVA analysis of plant growth parameters under varying soil conditions, fertiliser types, and dosages. With *P*-values less than 0.05 for both plant height and leaf count, the null hypothesis is retained. A statistically significant difference among the compared groups was observed, suggesting a significant impact of treatment choice on the observed differences.

Table 1. One-way ANOVA analysis for plant height (cm) and number of leaves per plant

Parameter	DF	SS	MS	*F*-Value	*P*-value
Plant height	11	756.25	68.75	6.687	0.00136*
Number of leaves	11	2603.13	236.65	5.509	0.00325*

DF: degree of freedom; SS: sum of squares; MS: mean of squares; *P < 0.01.

The highest plant dry weight of 23.6±2.1 g was achieved by the Struvite-Alkaline (II) treatment, while the lowest yield of 1.42±0.8 g was recorded by the Blank-Acidic treatment. The Struvite-Acidic (II) treatment, producing the second-highest dry weight and surpassing all NPK treatments, is also noteworthy, as shown in Figure 2(c). These results provide compelling evidence of a significant disparity in plant dry weight under different conditions. Understanding the role of fertilisers and soil pH is critical for optimising plant growth. Neina (2019) declared that soil pH affects the chemical forms and solubility of essential nutrients, such as N, P, K, and micronutrients, and thus determines how effectively plants can take up these elements; outside the optimal pH range many nutrients become less available, limiting plant growth and biomass yield. Also, the author stated that, in strongly acidic or alkaline soils, nutrient deficiencies and toxicities can develop even when sufficient fertilisers are applied, reducing nutrient use efficiency and crop performance. In the same context, Hariyadi *et al.* (2019) demonstrated that the combined treatment of dosage and application timing of fertilisers can greatly influence various aspects of plant development. Moreover, several studies have shown that struvite has the potential to enhance the growth of a variety of crops, including grasses, vegetables, maize, and fruits, compared to traditional water-soluble fertilisers (Liu *et al.*, 2013; Liu *et al.*, 2011; Szymańska *et al.*, 2020).

B. Nutrient Releasing Rate

1. Phosphate (PO_4) releasing rate

Figure 3 presents the results of the measurements taken for the release concentrations of PO_4 throughout the pot trial experiment. It was observed that struvite released nutrients at a slower rate over time compared to the NPK fertiliser. The highest initial release rate was recorded for NPK-Acidic (II), starting at approximately 260±5.0 mg/L and peaking at 350±10.0 mg/L by the 35th day. In contrast, a more modest initial releasing rate of around 190 mg/L is shown by NPK-Acidic (I), with a consistent and gradual increase until the 25th day. This is likely because struvite is thermodynamically stable at alkaline pH (Hertzberger *et al.*, 2020). A steady rise in PO_4 release over time indicates the continual supply of PO_4 by NPK-Acidic (I), with the quantity progressively increasing. Higher PO_4 release rates could potentially result from the utilisation of NPK fertiliser in acidic soil conditions. Degryse *et al.* (2017) found that struvite dissolution rates were nearly ninefold lower in alkaline soils (pH up to 8.5±0.05) compared to acidic soils (pH around 5.9±0.05) under plant-free conditions, with measured rates of 0.005 and 0.43±0.02 mg/day, respectively. This confirms the phenomenon of enhanced PO_4 dissolution from struvite under acidic conditions, where higher proton activity accelerates mineral breakdown and PO_4 release, improving nutrient availability, while alkaline conditions slow dissolution due to reduced proton concentration (de Soto *et al.*, 2023). The current findings are also consistent with the concept that soil pH influences both the activity and diversity of soil microorganisms, which play a vital role in the decomposition of fertilisers and nutrient release (Liu *et al.*, 2014).

Experimental sets with NPK fertiliser (NPK-Alkaline (I) and NPK-Alkaline (II)) showed intermediate PO_4 release rates under alkaline conditions, fluctuating between 210±10.0 and 90±8.0 mg/L, indicating a steady nutrient release.

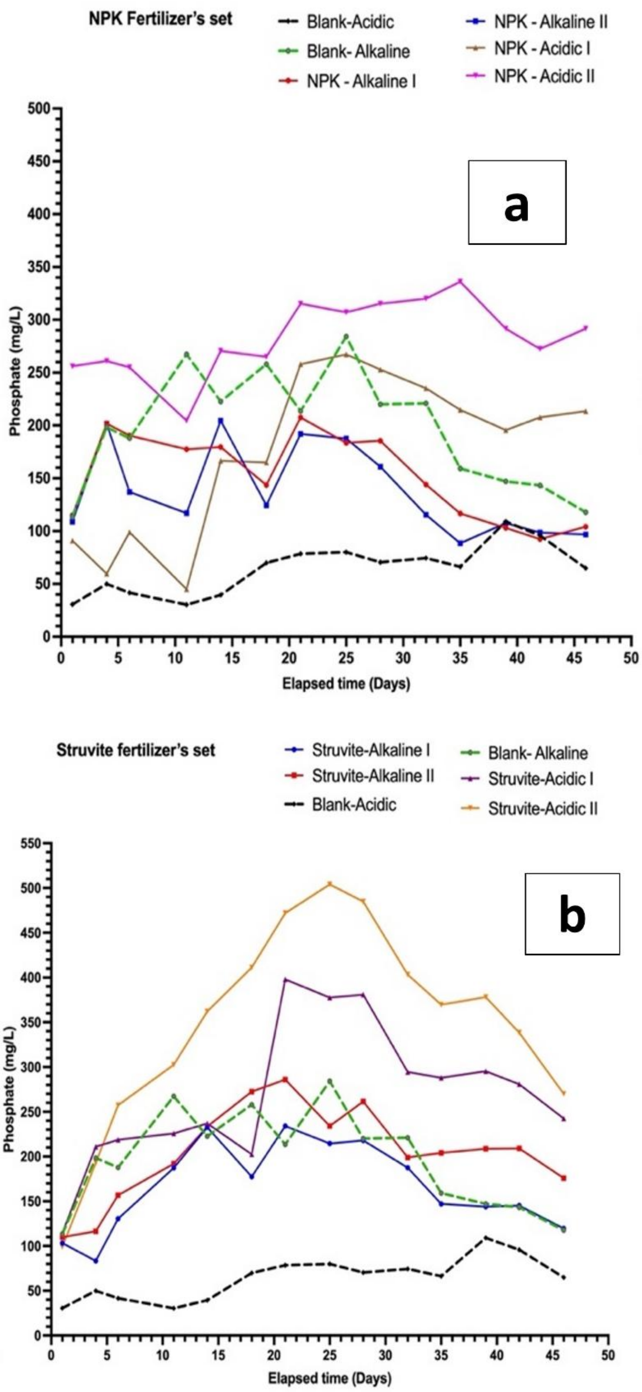


Figure 3. Phosphate (PO_4) releasing rates with (a) NPK fertiliser and (b) struvite fertiliser

A comparison of PO_4 release rates from struvite fertilisers in both acidic and alkaline soils is presented in Figure 3(b). The Struvite-Acidic (I) treatment shows a moderate increase initially, peaking at approximately 400±10.0 mg/L on the 18th day, followed by a gradual decrease. This suggests a front-loaded pattern of PO_4 release. In addition, Struvite-Acidic (II), with the highest rate among the examined sets, shows a rapid increase, peaking at around 510±10.0 mg/L by the 25th day. The dissolution rate of pure granular struvite is higher in acidic soils but decreases significantly in alkaline soils due to decreased solubility at pH values greater than 9.0 (Degryse *et al.*, 2017), highlighting the impact of soil pH on struvite behaviour and PO_4 release. Slower PO_4 release rates were observed for Struvite-Alkaline (I) and (II) compared to struvite in acidic soil, both starting at approximately 110±5.0 mg/L and gradually increasing. Peak values of approximately 290±5.0 mg/L and just below 250±5.0 mg/L are observed for Struvite-Alkaline (II) and (I) respectively. Compared with a study by Wang *et al.* (2023a), the current findings show that struvite releases nutrient dynamically, meeting the changing nutrient demands of crops and improving nutrient use efficiency. In addition to this benefit, it also reduces the environmental impact and the release of greenhouse gasses (Wang *et al.*, 2023b).

The one-way ANOVA results demonstrate that there are statistically significant differences in PO_4 release rates among the groups being compared. The analysis showed a substantial F-statistic of 17.72 with a P-value < 0.001, showing a highly significant difference in PO_4 release rates among the treatments. The results present compelling evidence that the treatments have a remarkable impact on nutrient release rates. Varied results between groups were observed when comparing PO_4 release rates in relation to soil condition, as presented in Table II. The t-test for NPK-Alkaline (I) and Struvite-Alkaline (I) yielded a P-value of 0.4543, which is greater than the typical significance level of 0.05, marked as "N.S." for "Not Significant". This indicates that the differences in nutrient release rates between these two groups are not statistically significant, leading to retain the null hypothesis. A shift in the statistical landscape is observed when analysing the PO_4 release rates of NPK-Alkaline (II) and Struvite-Alkaline (II). The t-test here yielded a P-value < 0.001, which suggests that the observed differences in PO_4 release rates between these two groups are statistically significant, allowing the null hypothesis to be rejected and confirming a substantial difference between the two groups.

Table 2. Statistical comparison of PO_4 release rates between groups

Soil pH	**NPK vs Struvite (one dosage)**	**NPK vs Struvite (doubled dosage)**
Alkaline	N.S.	P<0.001
Acidic	P<0.001	N.S.

N.S.: Not Significant

2. Nitrate (NO_3) releasing rate

Liu *et al.* (2014) classified most commercial fertilisers, including NPK, as quick-release fertilisers. These fertilisers become immediately available to plants when properly placed in soil with suitable moisture levels. Figure 4 illustrates the release patterns of NPK-Alkaline (I) and (II), with a surge in NO_3 release from day 1 to 5, peaking at around 200±8.0 mg/L and 170±9.0 mg/L, respectively. A gradual decrease in NO_3 release is observed thereafter, stabilising after 21 days, similar to the controls. The NPK-Acidic (II) shows the highest initial release rate, peaking at nearly 320±12.0 mg/L in the first 5 days, then decreasing rapidly to its minimum by day 21, with a slight initial increase. The NPK-Acidic (I) follows a similar trend, peaking at around 250±6.0 mg/L and a lower rate of 25±4.0 mg/L. Samples with both Blank-Alkaline and Blank-Acidic treatments exhibited stable NO_3 release rates, with a slight initial increase. Struvite-Alkaline (I & II) showed identical NO_3 release patterns, peaking at 110±5.0 mg/L, then aligning with control patterns from day 21. In their study, Min *et al.* (2019) reported that struvite has a slow nutrient-releasing rate that favours the assimilation of N and P in the soil solution. They also indicated a more uniform release pattern for struvite. This pattern signifies a notable uniformity in release rates when compared to the NPK fertiliser set, further emphasising the potential benefits of struvite as a fertiliser.

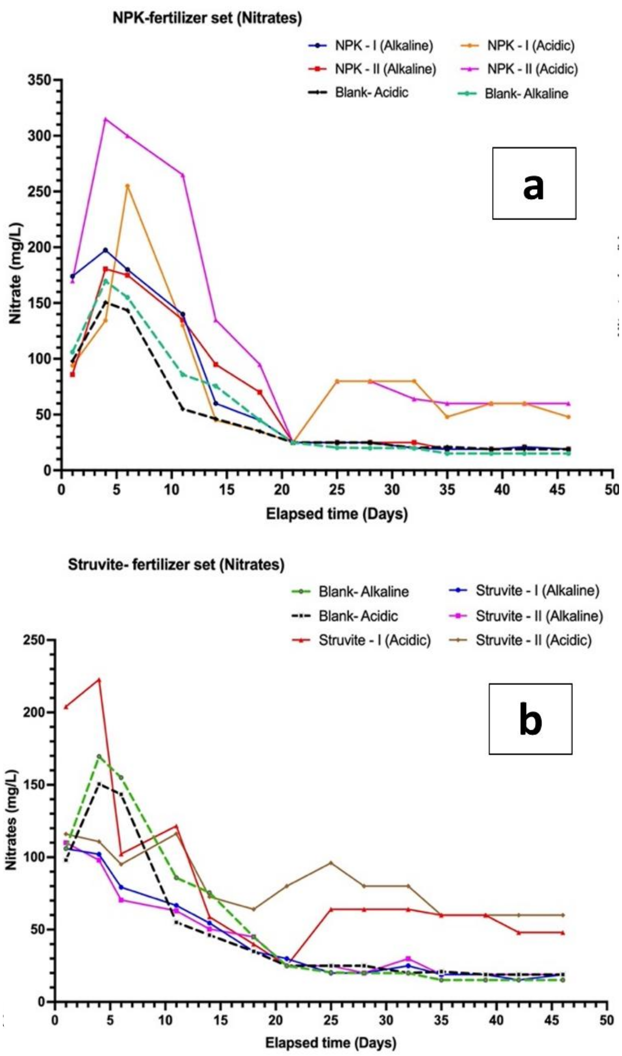


Figure 4. Nitrate (NO_3) releasing rates with (a) NPK fertiliser and (b) struvite fertiliser

Struvite-Acidic (II) shows a fluctuating NO_3 release pattern, increasing after two weeks and stabilising at 60 mg/L starting from day 35. Struvite-Acidic (I) exhibits higher NO_3 release rates during the first 5 days, surpassing Struvite-Acidic (II), followed by a sharp decrease until it reaches its lowest rate of nearly 30±2.0 mg/L, with a slight rebound at the end. Unlike other fertilisers, struvite releases nutrients consistently and gradually. However, in acidic soils, the release rate of its components (including N) accelerates. Talboys *et al.* (2016) emphasised that the effectiveness of struvite is comparable to that of water-soluble P fertilisers in alkaline, neutral, and mildly acidic soils. They also noted that the solubility of struvite increases in the presence of organic acids exuded by plant roots. This phenomenon may explain the considerable increase in NO_3 release rates observed in the Struvite-Acidic (I) & (II), compared with the other treatments.

As shown in Table 3, the nutrient content of the raw soil prior to fertiliser application was relatively low, particularly for PO_4 (75±2.0 mg/kg) and soluble NO_3 (284±5.0 mg/kg). After irrigation and plant growth, only slight changes were observed in the soil's baseline composition, with PO_4 and NO_3 values increasing modestly to 183±7.5 mg/kg and 201±5.9 mg/kg, respectively, while total N remained nearly constant.

Table 3. Soil nutrient measurements

Compound	**Method**	**Unit**	**Raw soil**	**Irrigated soil**
Phosphate as P	APHA4500-P-F	mg/kg	75±2.0	183±7.5
Total Nitrogen as N	APHA4500NORG-B, NO3-H	mg/kg	2,950±25.0	2,890
Nitrate (sol.)	APHA4500-NO3-H	mg/kg	284±5.0	201

Table 4. Statistical comparison of Nitrate (NO_3) release rates between groups

Soil pH	**NPK vs Struvite (Standard dosage) (I)**	**NPK vs Struvite (Double dosage) (II)**
Alkaline	N.S.	N.S.
Acidic	N.S.	N.S.

The results of the one-way ANOVA analysis, presented in Table 4, provide clear evidence that the treatments under consideration have a significant impact on N and P release rates. The analysis yielded an F-statistic of 2.873 and a corresponding P-value < 0.05, indicating a statistically significant difference in nutrient release rates among the treatments. This difference highlights the influence of treatments conditions on nutrients releasing rates. When examining the correlation between soil pH level and NO_3 release rates, a similar trend among different groups was noticed, as indicated in Table 4. The unpaired t-test produced a P-value greater than the typical significance level of 0.05, suggesting that there was no significant difference in nutrient release rates between the NPK and struvite treatments in both acidic and alkaline soils.

IV. CONCLUSION

This study assessed the performance of chemically precipitated struvite as a fertiliser for chili pepper under controlled pot conditions over a 60-day cultivation period. Statistically significant differences between struvite and conventional NPK fertiliser were observed for plant growth and nutrient release behaviour ($p < 0.05$). Struvite exhibited a slower and more sustained phosphate PO_4 release, with its effectiveness strongly influenced by soil pH. In contrast, NO_3 availability from struvite remained limited, confirming its primary role as a phosphorus-based fertiliser rather than a rapid nitrogen source. Chili pepper plants responded positively during the early vegetative growth stage, as reflected by changes in plant height, leaf number, and dry biomass. These findings highlight the importance of soil pH and application rate when evaluating struvite for agronomic use. However, the results are limited to short-term pot-scale conditions, and further field-based studies are required to assess long-term performance and crop yield.

Conflict of interest:

The authors declare no conflict of interest related to the manuscript.

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