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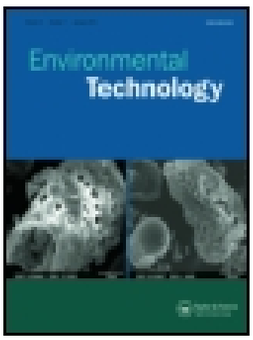
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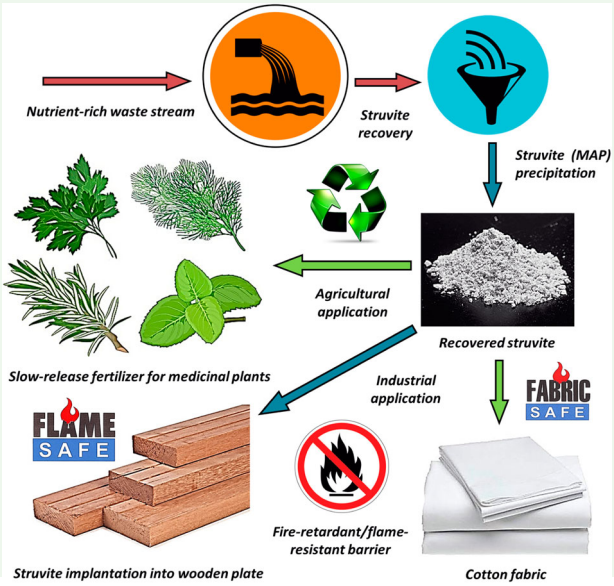
Utilization of struvite recovered from high-strength ammonium-containing simulated wastewater as slow-release fertilizer and fire-retardant barrier

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ABSTRACT

Sustainable uses of the struvite (magnesium ammonium phosphate hexahydrate, $MgNH_4PO_4{\cdot}6H_2O$, MAP) recovered from the synthetic wastewater, as a high-quality slow-release fertilizer for the growth of nine medicinal plants and a fire-retardant barrier on the flammability of cotton fabric and wooden plate, were explored in this study. The previous experimental results demonstrated that under the optimal conditions, about 98.7% of NH_4^+–N (initial NH_4^+–N = 1000 mg/L) could be effectively and successfully recovered from simulated wastewater in the form of MAP precipitate. Rates of increase in total fresh weights, total dry weights, and fresh heights of plants grown in soil fertilized with the struvite were determined as 67%, 52%, and 12% for valerian; 121%, 75%, and 18% for cucumber; 421%, 260%, and 47% for dill; 314%, 318%, and 27% for coriander; 432%, 566%, and 30% for tomato; 285%, 683%, and 26% for parsley; 200%, 225%, and 9% for basil; 857%, 656%, and 92% for rocket; and 146%, 115%, and 28% for cress, respectively, compared to the control pots. The microstructure, elemental composition, surface area, thermal behaviour, and functional groups of the grown crystals were characterized using SEM, EDS, BET, TGA-DTG-DSC, and FTIR analyses, respectively. Flammability tests and thermal analyses concluded that the dried and crumbled/implanted form of struvite used as a fire-retardant barrier demonstrated a remarkable flame-resistant behaviour for both cotton fabric and wooden plate. Findings of this experimental study clearly corroborated the versatility of struvite as non-polluting and environmentally friendly clean product for the sustainable usage in different fields



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Fire retardation; magnesium ammonium phosphate; medicinal plants; struvite

1. Introduction

Improperly managed nutrients result in severe environmental consequences (i.e. eutrophication of surface waters, disruption of soil stability, burning of plant roots, destroying of aquatic habitat, etc.) which are difficult to control using traditional implementations. Although conventional efforts for nutrient management offer some agro-based solutions (i.e. spraying of nutrient-

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rich wastewater on farm lands and discharging of it into receiving environment, etc.), increasing contamination in concentrated areas restricts the use of such short-term and temporary activities [1,2]. On the other hand, there will always be a certain demand for nutrients (particularly in large regions with phosphorus-deficient soils) to a greater or lesser extent for boosting the agricultural productivity [3]. However, due to mismanagement of nutrient resources, phosphorus scarcity may occur when the measure of supply cannot meet the measure of demand both in the short and long terms [4]. This may engender several problematic situations on multiple scales such as depletion of non-renewable phosphate reserves, constraints on food security and phosphorus fertilizers, and reduction in the population of aquatic organisms due to lack of nutrients (oligotrophication) [4]. Because the adverse impacts of nutrient pollution on the environment and human health cannot be neglected any longer, cost-effective and promising methods are needed for removal/recovery of excessive nutrients from waste streams to meet strict laws on environmental protection [5]. At this point, integrating the circular economy concept as an emerging strategy into nutrient management may help to achieve sustainable environmental protection in a productive and eco-efficient way [6]. This will diminish the contradiction between rapid economic growth and the shortage of nutrient scarcity and energy. Therefore, appropriate socio-economic measures could facilitate the reuse of nutrients, reduction of energy consumption, and mitigation of greenhouse gas emissions associated with agricultural activities [3].

Struvite or magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4{\cdot}6H_2O$, MAP) precipitation has been highlighted as an innovative, environmentally sound, and profitable physicochemical treatment method for recovery of recyclable constituents from nutrient-laden industrial discharges. In the literature, a substantial number of work has been performed for the removal and/or recovery of ammonium nitrogen (NH_4^+-N) and/or phosphate phosphorus ($PO_4^{3-}-P$) as struvite from various effluents such as animal waste stream [2,5,7–16], anaerobically digested discharge [17–21], synthetic wastewater [22–30], industrial effluent [31–34], landfill leachate [35–37], and human urine [38–41]. As seen from the previous studies that struvite precipitation has been broadly applied as an encouraging physicochemical treatment technique due to its efficacy in eliminating and/or recovering excess nutrients (e.g. nitrogen and phosphorus) from different kinds of wastes/wastewaters.

To the best of the authors' knowledge, an extensive review of the relevant literature reveals that the plurality of the struvite precipitation-based physicochemical treatability studies addresses not on the usability of struvite as a valuable raw material in other industrial processes, but rather on the effect of the process-related conditions (i.e. magnesium or phosphate sources, reaction pH, temperature, doses and molar ratios/combinations, stirring speed and time, etc.) on the removal/recovery of nutrients from different types of wastewaters. Despite of several greenhouse studies have been previously conducted on the fertilizer potential of the struvite, most of them are related to vegetables (e.g. cabbage, chard, spinach, broad bean, maize, tomato, lettuce, pepper, etc.), and there is a still gap in the literature concerning the cultivation of different types of herbs and medicinal/therapeutic plants. More importantly, there is another apparent gap in the relevant field concerning the usability of struvite as fire-retardant/flame-resistant barrier. Although the previous studies cited above (as well as other investigations conducted on this subject) have made significant contributions to relevant literature, the present study is a new attempt to fulfil the mentioned gap by focusing upon other beneficial properties of the recovered struvite.

Based on the foregoing facts, the specific objectives of this study were as follows: (1) to explore the ameliorative effect of the struvite as a high-quality slow-release and multi-nutrient fertilizer in cultivation of different medicinal plants (valerian (*Valeriana officinalis*), cucumber (*Cucumis anguria* L.), dill (*Anethum graveolens*), coriander (*Coriandrum sativum*), tomato (*Lycopersicon esculentum*), parsley (*Petroselinum hortense*), basil (*Ocimum basilicum*), rocket (*Eruca sativa*), and cress (*Lepidium sativum* L.)) by a series of pot trial experiments; (2) to examine the physical morphologies of the seeds of each plant species; (3) to investigate the flame-retardant potential of dried and crumbled/implanted form of the struvite for both cotton fabric and wooden plate by performing a set of flammability tests; (4) to make an assessment of literature findings regarding the fertilizing potential of struvite on the growth of different types of potted plants; and (5) to highlight the universal attractiveness and versatility of the struvite particularly for agricultural and fire management activities in rural areas.

2. Materials and methods

2.1. Previous findings and ongoing research

The experimental conditions conducted in preparation of synthetic wastewater and $MgNH_4PO_4{\cdot}6H_2O$ (MAP) precipitation tests, and the economic aspects of the process were fully documented within the framework of our

comprehensive feasibility analysis [29]. To recover high-strength ammonium nitrogen (NH_4^+—N = 1000 mg/L) in the form of struvite from the simulated fertilizer wastewater, a total of 624 physicochemical treatability experiments were previously performed using six chemical combinations ($MgCl_2{\cdot}6H_2O + KH_2PO_4$, $MgCl_2{\cdot}6H_2O + NaH_2PO_4{\cdot}2H_2O$, $MgSO_4{\cdot}7H_2O + KH_2PO_4$, $MgSO_4{\cdot}7H_2O + NaH_2PO_4{\cdot}2H_2O$, $MgO + KH_2PO_4$, $MgO + NaH_2PO_4{\cdot}2H_2O$) at thirteen different Mg^{2+}:NH_4^+—N:PO_4^{3-}—P molar ratios, including the stoichiometric ratio (1:1:1), overdose (1.2:1:1 1.5:1:1 1.8:1:1 1:1:1.2 1:1:1.5 1:1:1.8) and underdose (0.2:1:1, 0.5:1:1, 0.8:1:1 1:1:0.2 1:1:0.5 1:1:0.8) at different pH levels ranging from 5.0 to 11.0. Previous findings can be summarized that the optimal operating conditions were determined with a chemical combination of $MgO + NaH_2PO_4{\cdot}2H_2O$, a Mg^{2+}:NH_4^+—N:PO_4^{3-}—P molar ratio of 1.2:1:1, a reaction pH of 9.0, and a total mixing time of 15 min. The experimental results concluded that under the optimal conditions, about 98.7% of NH_4^+—N could be effectively and successfully eliminated from the synthetic fertilizer wastewater [29].

Following to the previous experiments (MAP precipitation-based physicochemical treatability studies), in the present research, nine different test plants, which are highly used in alternative medicine and cultivated in semi-arid agro-climatic conditions of Turkey, were simultaneously tested to explore the ameliorative effect of the MAP precipitate as a high-quality slow-release fertilizer in a series of lab-scale greenhouse experiments. In the present study, utilization of the obtained product (dried and crumbled/implanted form of the optimal MAP precipitate or struvite) as a fire-retardant barrier and its flame-resistant behaviour were also investigated for both cotton fabric and wooden plate by performing a set of flammability tests.

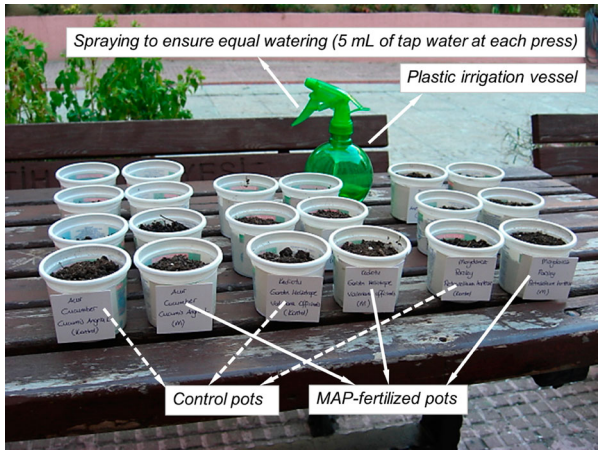


Figure 1. Photograph of the present plant cultivation set-up.

2.2. Assessment of physical characteristics of plant seeds

To determine the specific weights (γ_s) of the seeds of each plant species, 5 mL of glass graduated cylinders were consecutively filled with each plant seed and weighed. Then the tare weight of the cylinder was subtracted from measured weights, and the remained values were divided by the sample volume (5 mL) to obtain the specific weights of the seeds. An electronic precision analytical balance (Kern PCB 350-3 (Germany), reading precision: 0.001 g, maximum measuring range: 350 g, reproducibility: 0.002 g, linearity: ±0.005 g; temperature range: +5°C to + 35°C) was used for weighing operation. Additionally, a stereo microscope (MSL4000-10/30-IL-TL, A. KRÜSS Optronic GmbH, Hamburg, Germany) combined with a Samsung Galaxy S3 digital camera was used to image the physical morphologies of the seeds of each plant species. The results are presented in Section 3.2.

2.3. Greenhouse experiments

The fertility of the MAP precipitate obtained under the optimum operating conditions [29] was explored in a set of greenhouse experiment (Figure 1). Nine quick-growth medicinal plants, such as valerian (*Valeriana officinalis*), cucumber (*Cucumis anguria* L.), dill (*Anethum graveolens*), coriander (*Coriandrum sativum*), tomato (*Lycopersicon esculentum*), parsley (*Petroselinum hortense*), basil (*Ocimum basilicum*), rocket (*Eruca sativa*), and cress (*Lepidium sativum* L.), were selected for the present agricultural study. The plant seeds free from disease were purchased from a local herbal market in Eminonu, Istanbul, Turkey. Prior to any experiment, all plant seeds were screened to remove undesirable materials such as stones and other impurities and kept in an airtight polythene bags until needed for analysis [42]. It is noted that details of medicinal impacts of the studied plants were fully elaborated in the previous studies [42–51]. Therefore, without going into their therapeutic details, this research only provided information on the sustainable aspects of the present greenhouse process to evaluate the fertilizing quality of the struvite on the growth of the studied medicinal plants.

Soil was used as a raw solid medium for germination and growth of the selected plants. According to the dimensions of plastic pots (upper diameter × lower diameter × height = Ø75 × Ø52 × 62.5 mm), 200 g of soil were filled in each of the pots. The characterization (supplied by the manufacturer) of the used raw soil were pH 5.5–6.5, electrical conductivity (EC) 0.50–0.80 mmhos/cm

or dS/m, nitrate nitrogen (NO_3-N) 50–100 mg/kg, phosphorus (P) 10–20 mg/kg, potassium (K) 40–100 mg/kg, calcium (Ca) 30–50 mg/kg, and magnesium (Mg) 10–20 mg/kg.

According to various online agricultural platforms (not cited herein), required fertilizer application rates of macro elements (N, P, K) for the production of the studied medicinal plants (in Turkey) are recommended between 3 and 25 g N/m^2 of soil (equivalent to 3–25 kg N per decare, 1 decare = 1000 m^2), 0.35–5.24 g P/m^2 of soil (equivalent to 0.8–12 kg P_2O_5 per decare), and 2.16–12.45 g K/m^2 of soil (equivalent to 2.6–15 kg K_2O per decare). To determine the required MAP (struvite) dose to be fertilized into the studied amount of solid media (soil), the average of the suggested ranges for fertilizer application and the average amounts of macro elements available in the solid medium were considered in the present study. The highest safe struvite dose that would be applied as a slow-release fertilizer into 200 g of soil was determined approximately 0.50 g on the nitrogen-basis from the following expressions:

$$W_{MAP} = \frac{[(R_F \cdot SA_F) - C_{ME}] \cdot MW_{MAP} \cdot SF}{M_{ME}} \quad (1)$$

$$\frac{\{[(1.4\ \text{mg N/cm}^2\text{of soil}) \times (26.42\ \text{cm}^2\text{of soil/pot})] - (15\text{mg N/pot})\} \times (245000\ \text{mg MAP/mole MAP}) \times 1.3}{(14000\ \text{mg N/mole MAP})} \cong \frac{0.50\ \text{g MAP}}{\text{pot}} \quad (2)$$

where W_{MAP} is the safe MAP dose to be fertilized into the soil (g MAP per pot); R_F is the average fertilizing rate that is needed to be applied (herein R_F = 1.4 and 0.28 mg/cm^2 of soil for N and P, respectively); SA_F is the size of surface area to be fertilized (herein SA_F = 26.42 cm^2 of soil per pot for top surface diameter (58 mm) filled with soil); C_{ME} is the average amount of the macro element available in the soil (herein C_{ME} = 15 and 3 mg for N and P per pot (for 200 g of soil), respectively); M_{ME} is the mass of the macro element per mole of fertilizer (M_{ME} = 14 and 31 g for N and P per mole of the struvite, respectively); MW_{MAP} is the molecular weight of struvite compound ($MgNH_4PO_4 \cdot 6H_2O$, magnesium ammonium phosphate hexahydrate (MAP), MW_{MAP} = 245 g/mole); and SF is the safety factor (herein SF is considered as 1.3). It is noted that no external K source was added into the growing medium, except the existed amount in the soil.

In the cultivation of the studied medicinal plants, following steps were conducted [2,5,14,35]: (i) each plastic pot was filled with the soil; (ii) about 2 cm of top layer was excavated from the pots; (iii) pre-weighted MAP precipitate (herein W_{MAP} = 0.50 g for 200 g of soil in each pot or a dosage of 2.5 g struvite/kg soil) was mixed into the soil prior to seeding; (iv) 50 mL of tap water was added evenly over the surface of each pot; (v) pre-weighted plant seeds (each of 1 g) were laid evenly on the removed soil surface; (vi) plant seeds were covered with the removed soil, and surface of the refilled solid media was then kindly pressed down using the reverse side of a teaspoon; (vii) a second 50 mL of tap water was poured uniformly over the seeded and refilled surface.

Pots were randomly placed in a naturally illuminated growth environment under atmospheric conditions, so that sufficient ultraviolet radiation was directly provided by daylight. According to temperature and humidity of the ambient air, tap water was sprayed into each pot (5 mL at each press) from a plastic irrigation vessel (Figure 1) to ensure equal watering to all plants during 25-day cultivation process. To investigate the fertilizing effect of the MAP sludge (struvite) obtained under the previous optimal conditions (a chemical combination of $MgO + NaH_2PO_4 \cdot 2H_2O$, a Mg^{2+}:NH_4^+—N:PO_4^{3-}—P molar ratio of 1.2:1:1, a reaction pH of 9.0, and a total mixing time of 15 min) on the plant growth, all medicinal plants were harvested on the 25th day after seeding.

Prior to harvesting, all studied plants in both MAP and control pots were sprayed with deionized water (supplied from a Sartorius Stedim Biotech ultrapure water system) to wash the dust off [2,5,14,35]. After sun-dried in ambient conditions [42], the five tallest plant individuals (including their roots) in both MAP and control pots were gently picked up for statistical comparison of their fresh heights. Thereafter, all harvested samples were weighed (using a Kern PCB 350-3 electronic precision analytical balance, Germany) before and after drying at 105°C for 24 h (using an Electromag M6040 P dry-air sterilizer oven, USA) to determine the total fresh and total dry weights of each plant species, respectively. The foregoing agricultural period was followed by harvesting process, statistical analysis, and preparation of fire-retardant barrier performed within the scope of a set of flammability tests. The results are presented in the Sections 3.2 and 3.3.

2.4. Analytical methods used in characterization of struvite

The crystal morphology of the struvite sample (MAP) was observed using a Scanning Electron Microscopy (SEM, Zeiss Evo LS 10, Germany) and the analysis of MAP composition was conducted by Energy Dispersive Spectroscopy (EDS) with an accelerating voltage of 7.5 kV. Moreover, Fourier Transform Infrared (FTIR) spectrum of the MAP was recorded using a Bruker, Alpha FTIR spectrograph in the wavelength range of 500–3900 nm.

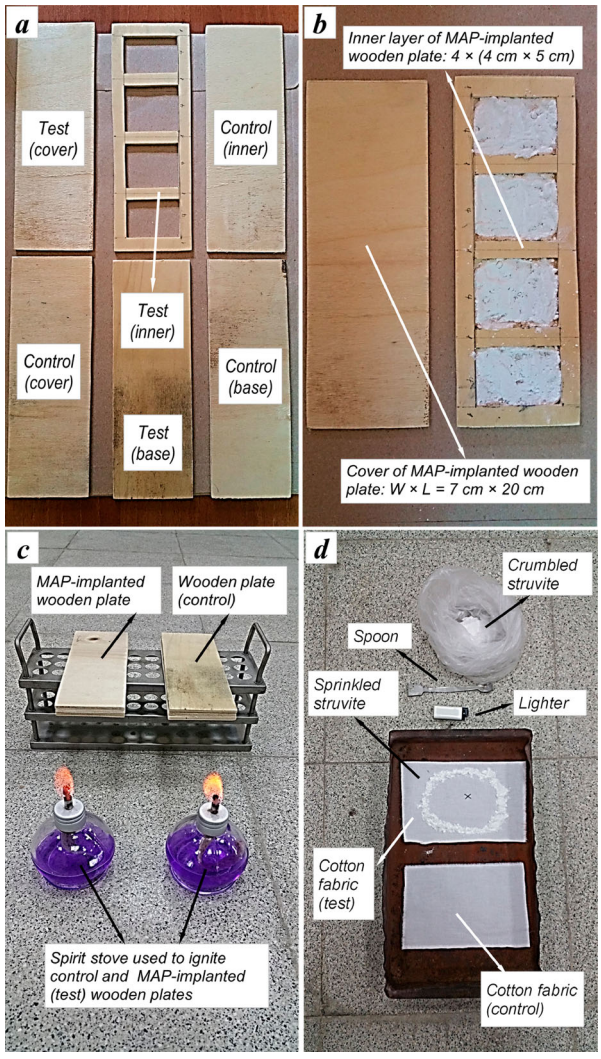


Figure 2. Photographs illustrating steps of the implemented flammability test: (a) Preparation of wooden plates; (b) Struvite implantation; (c) Flammability set-up for wooden plates; (d) Preparation of cotton fabric specimens.

Combustion test of MAP was implemented applying thermal analysis method. For this purpose, TA Instruments SDT Q600 model thermal analyzer was used. For this, 5 mg of sample was heated from ambient (room temperature) to 900°C with a constant heating rate of 10°C min^{-1} under dry air flow of 40 mL min^{-1}. The thermal data produced from the software of the thermal analyzer was used to derive the curves of Thermogravimetric Analysis (TGA), Derivative Thermogravimetry (DTG), and Differential Scanning Calorimetry (DSC). These curves are relevant to combustion characteristics and the burning profiles of the sample.

Furthermore, Quantachrome NovaWin2, NOVA Instruments was used to determine Brunauer–Emmett–Teller (BET) surface area of MAP. The BET surface area was obtained from nitrogen adsorption isotherms at 77 K.

2.5. Fire retardation studies (flammability tests)

In this study, another sustainable use of the struvite as a fire-retardant barrier was explored for both cotton fabric and wooden plate by conducting a set of flammability tests. To investigate its flame-resistant property, dried and crumbled/implanted form of the optimal MAP precipitate was used for the burning process. In the first step, three identical wooden plates (width × length × thickness = 70 × 200 × 4 mm) were prepared as test and control panels. While four equal parts (40 × 50 × 4 mm) were first cut out from the middle (or inner) layer of the test plate for struvite implantation, no action was taken on the middle layer of the wood panel used for the control purpose (Figure 2a). The crumbled struvite was implanted into cut-out spaces after the middle layer was adhered onto the base layer (Figure 2b). Thereafter, a flammability set-up, which was consisted of two three-layered wooden plates (control and test) and two spirit stoves for ignition of them, was prepared for the burning process (Figure 2c). It is noted that although a preliminary flammability analysis was performed using a small piece of cotton fabric in the previous work of the first author [5], a more complicated flammability test related to struvite implantation into a wooden panel was first conducted within the scope of this study.

In the second step, two pieces of cotton fabric were cut into approximately 17 × 27 cm rectangles to be used in the present flammability test. The centre of each cotton fabric was marked as '×' with a pen to represent a critical point in the burning process. One of them was selected as the control, and the other was used as the test fabric. After the preparation of fabric specimens, dried and crumbled struvite was sprinkled around the marked point of the test fabric using a spoon to represent a circular fire barrier with a diameter of about 14 cm (Figure 2d).

The present flammability test was conducted under controlled laboratory conditions, and the total burning time was measured with a stopwatch. After the materials were subjected to a flame ignition for a specified period (approximately 12 min for wooden plates and 2 min for cotton fabrics), they were extinguished, and the flame was completely removed. At the end of the burning of wooden plates and cotton fabric specimens, the exhaust ventilation was provided for about 20 min to ensure that toxic gases were taken away from the environment in which the experiment was performed.

2.6. Statistical analysis and computational procedure

StatsDirect (V2.7.2, StatsDirect, Ltd., Altrincham, Cheshire, UK) software package operating on a PC platform

(Casper Excalibur, Intel® Core™ i7-7700HQ CPU, 2.81 GHz, 16 GB of RAM, 64-bit) was used for the statistical analysis of the experimental data. In all calculations, spreadsheets of Microsoft® Excel® 2016 (Microsoft Inc., Redmond, WA) running under Windows 10 operating system was used as an open database connectivity data source. An alpha (α) level of 0.05 (or 95% confidence) was used to determine the statistical significance in all analyses. Fresh-dry weights and fresh sprout heights used as quantitative measures of the fertilizing value of the MAP precipitate were statistically evaluated by means of appropriate statistical tests.

Prior to applying parametric (unpaired (or two-sample) *t* test and *F* (variance ratio) test) or non-parametric tests (the Mann–Whitney U (or the Wilcoxon rank-sum) test and the Kruskal–Wallis test with the Dwass-Steel-Chritchlow-Fligner method), the Shapiro–Wilk *W* (named after Samuel Sanford Shapiro and Martin Wilk) and the Levene's (named after Howard Levene) tests were consecutively conducted as preconditions to ensure that the experimental subsets had a normal or non-normal distribution, and variances (or standard deviations) of the paired groups were homogeneous or unequal. When the supposition of normality and confirmation of the equality/homogeneity of variances were corroborated simultaneously, a parametric test (unpaired *t* test or *F* (named in honour of Sir Ronald Fisher by George W. Snedecor) test) was implemented. In case of the observed data sets were not normally distributed, a non-parametric test was applied. Mann–Whitney (MW) *U* test (named after Henry Berthold Mann and Donald Ramson Whitney, a non-parametric test that is used to compare two population means that come from the same population, and it is also used to test whether two population means are equal or not) or the Kruskal–Wallis (KW) test (named after William Kruskal and W. Allen Wallis) was used to compare the considered subsets (i.e. measured data obtained from MAP pots and control pots).

Mann–Whitney *U* test involves the calculation of the following test statistics (U_x, U_y, and U) for datasets $x_i = \{x_1, x_2, \ldots, x_n\}$ and $y_i = \{y_1, y_2, \ldots, y_n\}$:

$$U = \min(U_x, U_y) = \begin{cases} U_x = n_x n_y + \dfrac{n_x(n_x+1)}{2} - R_x \\ U_y = n_x n_y + \dfrac{n_y(n_y+1)}{2} - R_y \end{cases} \quad (3)$$

where n_x is the size of dataset *x*, n_y is the size of dataset *y*, and R_x is the adjusted rank sum for dataset *x*, and R_y is the adjusted rank sum of dataset *y*. If the observed value of $U \leq U_{\text{critical}}$ then the test is significant (at the α level), the null hypothesis (H_0: There is a no difference between the ranks of the two samples) is rejected in favour of alternative hypothesis (H_1: There is a difference between the ranks of the two samples).

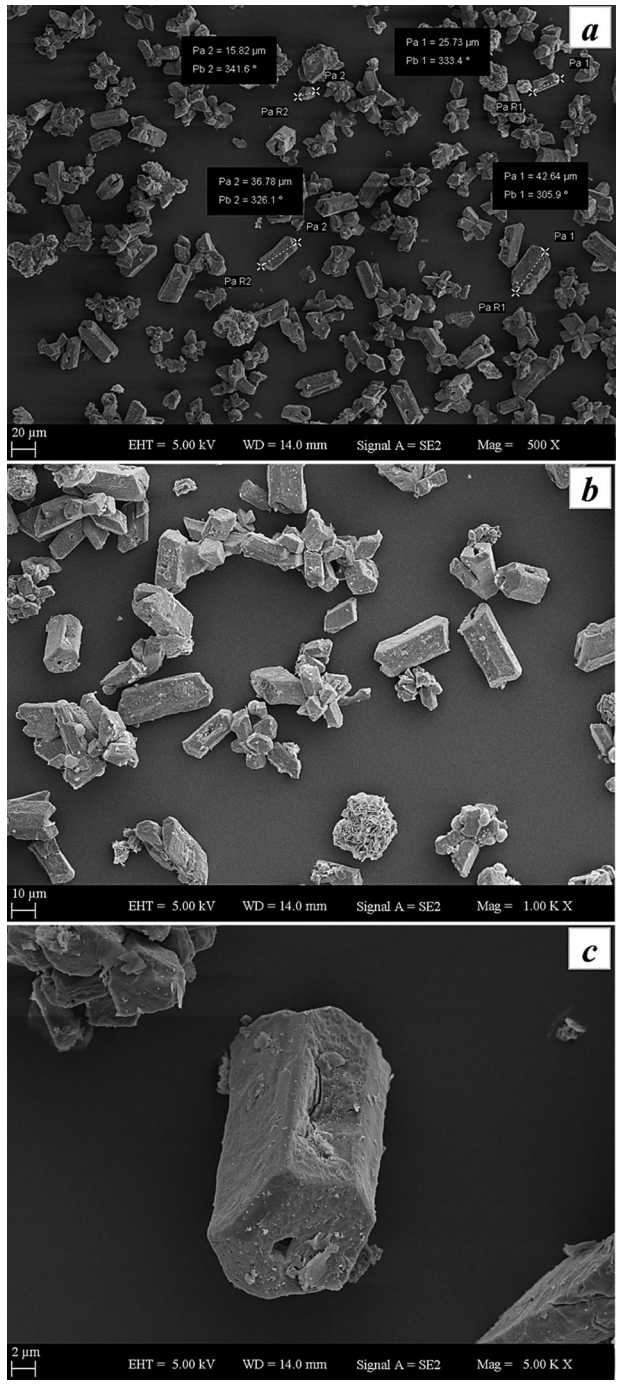


Figure 3. SEM micrographs of struvite crystals recovered from high-strength ammonium-containing simulated wastewater ($MgO + NaH_2PO_4{\cdot}2H_2O$, pH = 9.0, Mg:N:P = 1.2:1:1).

For large samples (i.e. $n_x > 20$ and $n_y > 20$), the *U* statistic is approximately normally distributed: $N(\mu_U, \sigma_U)$, where μ_U and σ_U are the mean and standard deviation of *U*. In that case, the standardized value of *z* statistic (i.e. for a two-tailed test and a significance level of $\alpha = 0.01$, $z_{\text{critical}} = \pm 2.58$) can be calculated and interpreted

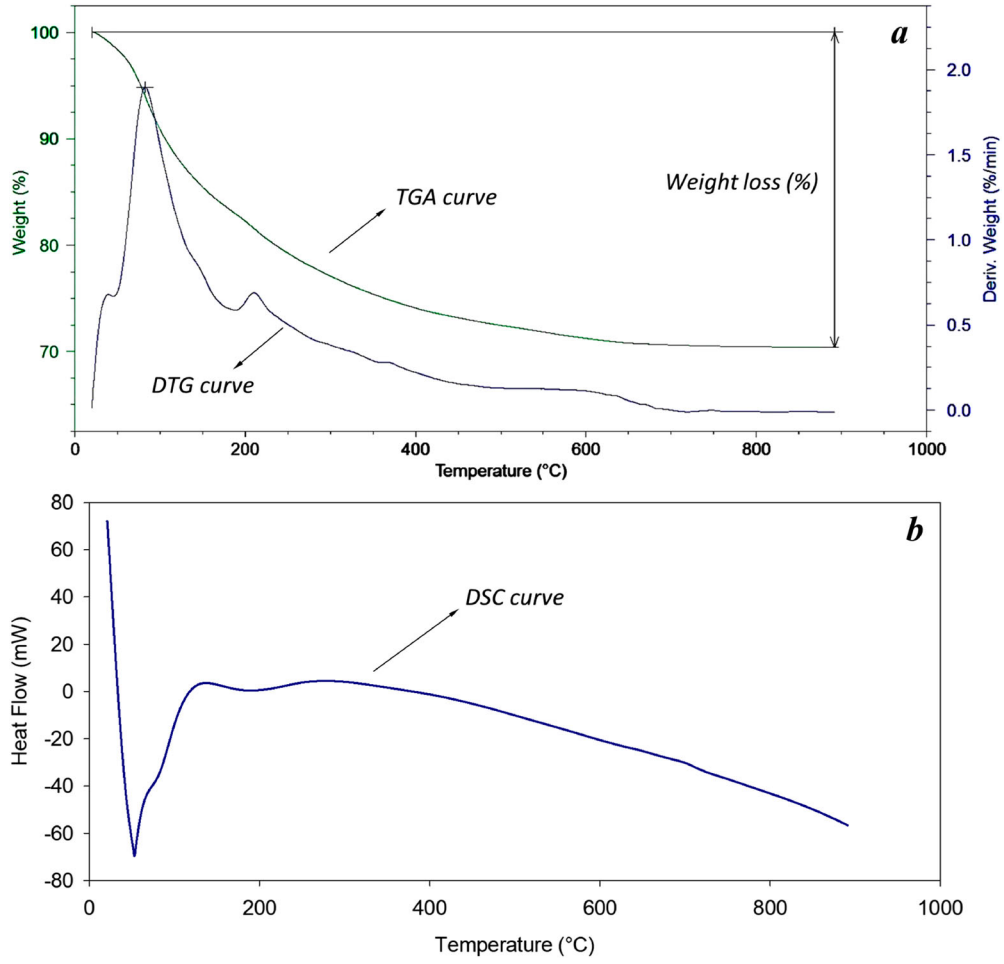


Figure 4. (a) TGA and DTG curves; and (b) DSC curve of struvite recovered from high-strength ammonium-containing simulated wastewater ($MgO + NaH_2PO_4{\cdot}2H_2O$, pH = 9.0, Mg:N:P = 1.2:1:1).

(for the $z_{critical}$ value > 0) as follows:

$$z = \frac{U - \mu_U}{\sigma_U} = \frac{U - (n_x n_y)/2}{\sqrt{(n_x n_y (n_x + n_y + 1)/12)}} \rightarrow |z| = \begin{cases} |z| > z_{critical} \rightarrow p < \alpha \rightarrow H_1 \\ |z| < z_{critical} \rightarrow p > \alpha \rightarrow H_0 \end{cases} \quad (4)$$

Test results were assessed with various descriptive statistics such as appropriate *p* values, *t* statistics, *F* statistics, combined (or pooled) standard errors (se_p), and power values (PW or probability of detecting a true effect for 5% significance) to reflect the statistical significance between samples.

3. Results and discussion

3.1. Properties of struvite recovered from simulated wastewater

Figure 3a–c illustrates the SEM micrographs of struvite crystals recovered from high-strength ammonium-containing simulated wastewater. All the SEM images illustrate irregular-shaped crystals with various sizes. The most common morphology observed in different morphologies of grown crystals was the hexagonal prism shaped. Besides irregular shaped crystals, uniform hexagonal prism shaped crystals with a maximum length of 42.64 µm and a radius of 5 µm can be observed in the sample micrograph.

The chemical composition of the MAP was also analyzed by EDS. The analytical result indicated that it had a composition 4% N, 23.2% Mg, and 27.6% P (weight %), when a molar ratio of Mg^{2+}:NH_4^+—N:PO_4^{3-}—P = 1.2:1:1 was applied. BET surface area of MAP sample was found as 16.35 m^2/g.

As can be seen from TGA and DTG curves in Figure 4a, struvite sample only loss 29% of its weight during the combustion process reaching up to 900°C. It is important to evaluate DSC heat flow curve of sample produced from TGA and DTG thermogravimetric curves (Figure 4b). Heat flow curve shows the endothermic and exothermic regions that take place during combustion

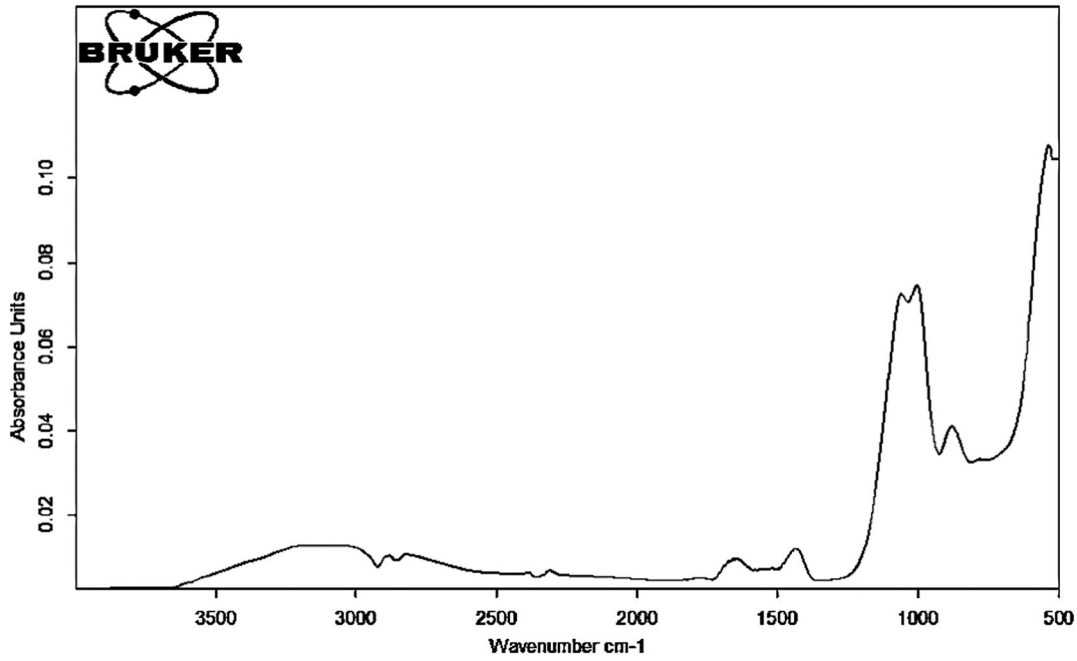


Figure 5. FTIR spectrum of the struvite recovered from high-strength ammonium-containing simulated wastewater ($MgO + NaH_2PO_4 \cdot 2H_2O$, pH = 9.0, Mg:N:P = 1.2:1:1).

as temperature increases. The negative heat flow represents endothermic phenomena, while the positive heat flow shows the exothermic phenomena. As can be seen from Figure 4a that moisture removal formed the endothermic heat flow region at temperatures around 34–119°C. Then, no endothermic or exothermic heat flow peaks were observed until temperature reaches to 900°C. Exothermic peak means the combustion of material. And it can be concluded that struvite is one of important fire-retardant barrier materials. This material doesn't contain any carbon compounds which can be combusted, while it contains phosphate compounds which are used in fire-retardant materials. As a result, TGA, DTG, and DSC curves (Figure 4), which are relevant to combustion characteristics and the burning profiles of the sample, confirmed the fire-retardant property of struvite.

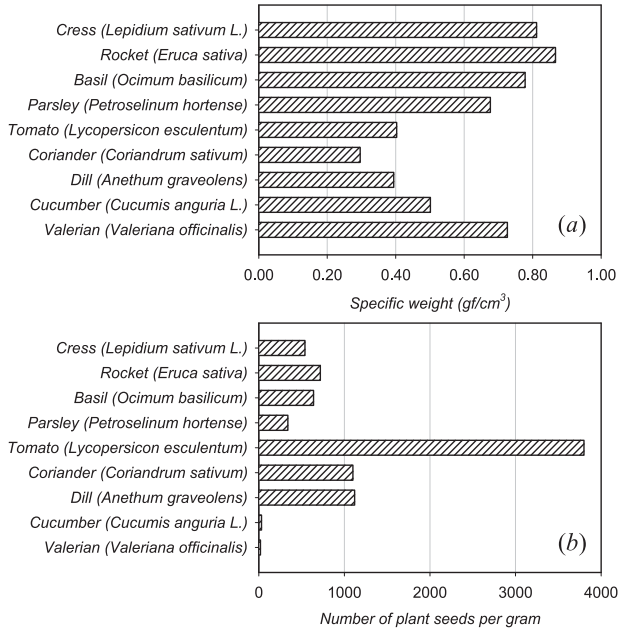


Figure 6. (a) Specific weights of the seeds of each plant species; (b) Number of seeds per gram.

The Fourier transform infrared (FTIR) spectrum, which is depicted in Figure 5, provides to find out the radicals in the crystal and the type of bonds that exist between the elements. In the FTIR spectrum, the stretching vibration of PO_4^{3-} units was found to be at 1058, 1003, and 533 cm^{-1}. The H–O–H stretching vibrations of water molecules of crystallization were observed between 3000 and 3500 cm^{-1} and the H–O–H stretching vibrations of cluster of water molecules of crystallization were at 2375 cm^{-1}. The H–O–H bending modes of vibrations were exhibited at 1647 cm^{-1} and the wagging modes of vibration of coordinated water at 878 cm^{-1}. NH_4^+ unit was observed at 1433 cm^{-1}. Also, the absorption occurring at 2900 cm^{-1} is due to NH_4^+ ion. The FTIR technique proves the presence of water of hydration, N–H bond, P–O bond, NH_4^+, and PO_4^{3-} ions. As a result, the FTIR spectrum of the struvite recovered from high-strength ammonium-containing simulated wastewater

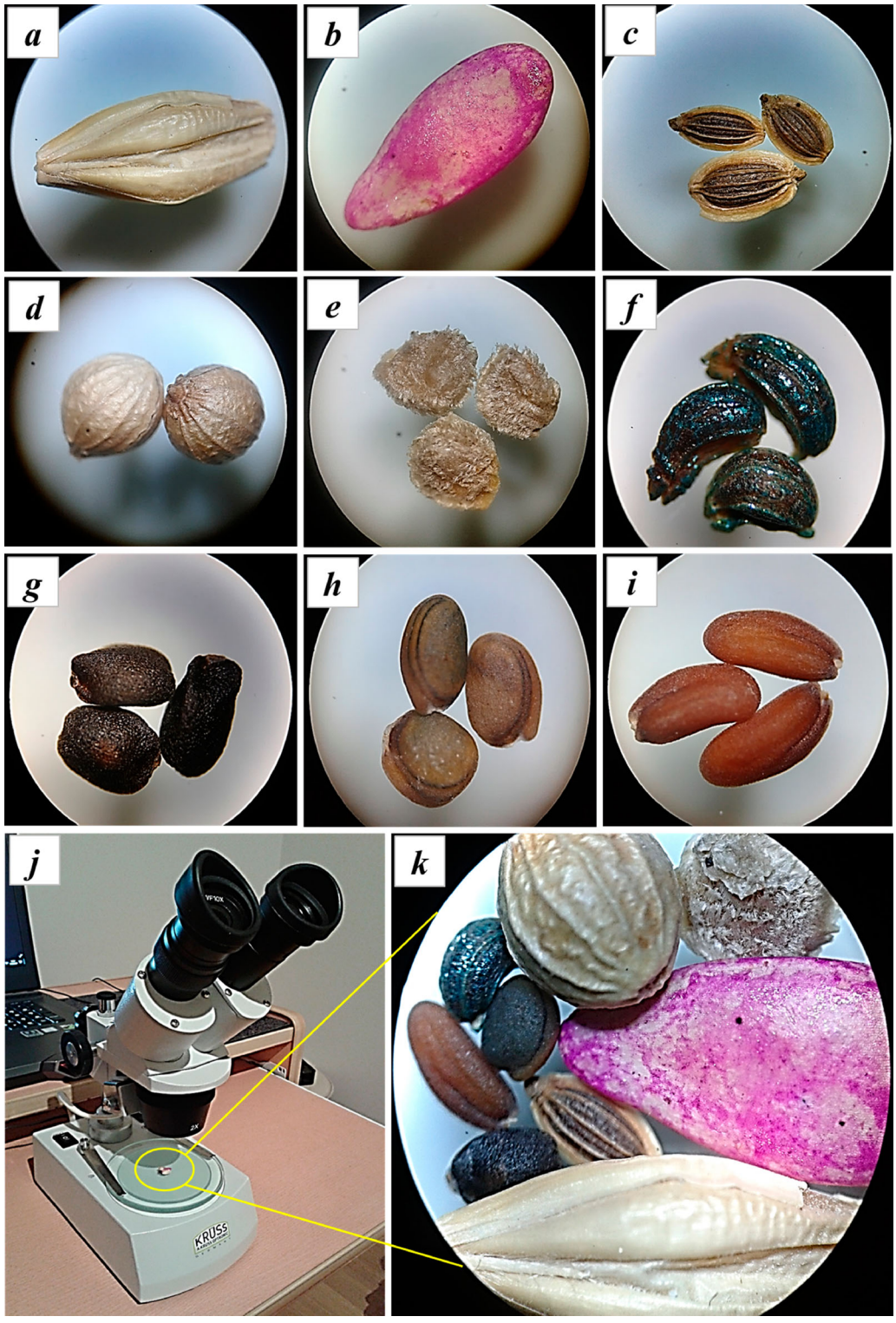


Figure 7. Stereo microscope photographs of each plant seed obtained at 20 times magnification: (a) Valerian (*Valeriana officinalis*); (b) Cucumber (*Cucumis anguria* L.); (c) Dill (*Anethum graveolens*); (d) Coriander (*Coriandrum sativum*); (e) Tomato (*Lycopersicon esculentum*); (f) Parsley (*Petroselinum hortense*); (g) Basil (*Ocimum basilicum*); (h) Rocket (*Eruca sativa*); (i) Cress (*Lepidium sativum* L.); (j) Stereo microscope (MSL4000-10/30-IL-TL); (k) Comparative image showing the plant seeds together.

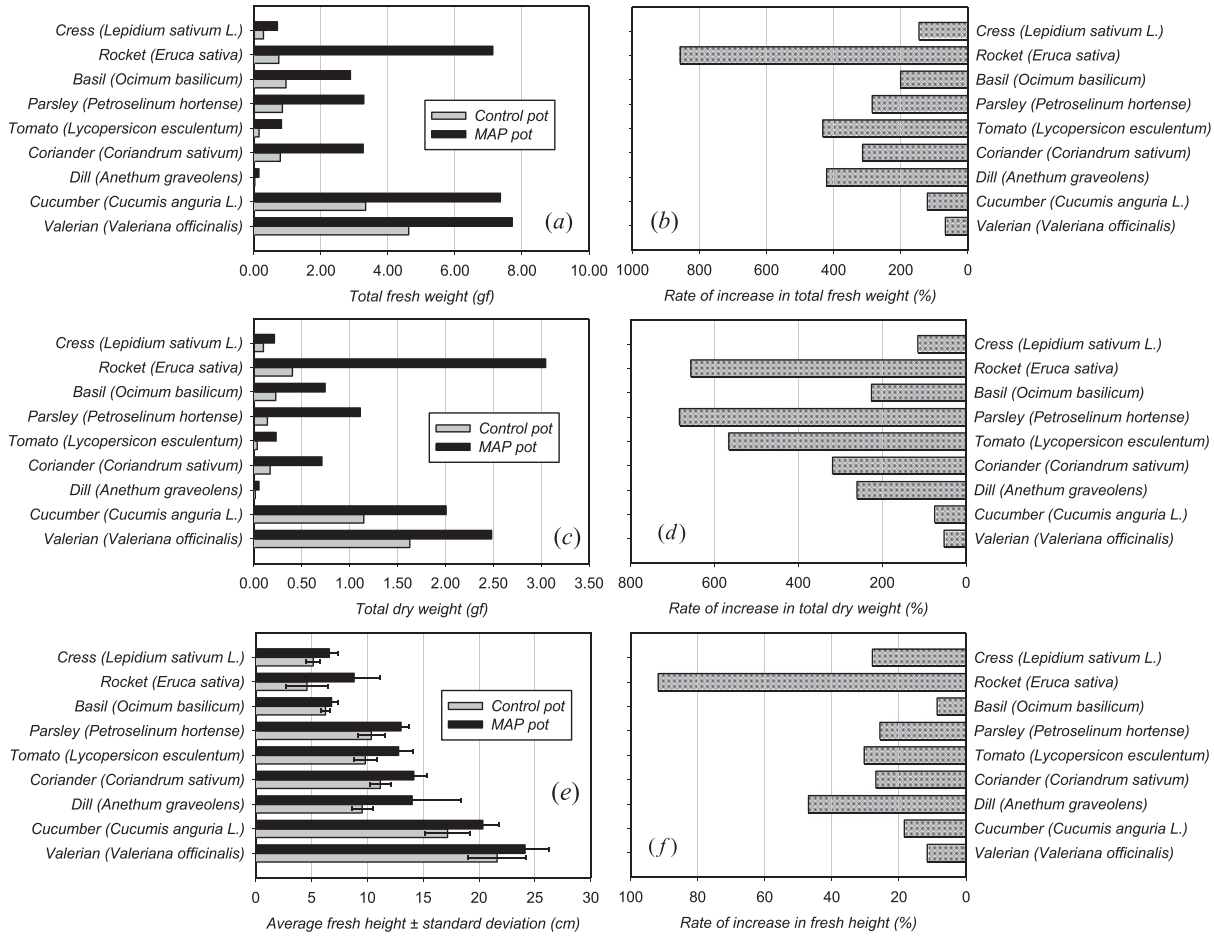


Figure 8. Comparison of growth parameters of the harvested medicinal plants for the control and MAP groups after 25 days of cultivation period: (a) Total fresh weight; (b) Rate of increase in total fresh weight; (c) Total dry weight; (d) Rate of increase in dry weight; (e) Average fresh height ± standard deviation; (f) Rate of increase in average fresh height.

confirms that it is magnesium ammonium phosphate hexahydrate [52,53].

3.2. Physical morphologies of medicinal plant seeds

According to the results of the present analysis (Figure 6), the highest value ($\gamma_s \approx 0.867$ gf/cm$^3 \approx 867$ kgf/m$^3 \approx 8502.7$ N/m^3) in terms of specific weight was found for the rocket (*Eruca sativa*), and the highest value ($n_s \approx$ 3800 seeds per gram) in the number of seeds per gram was obtained for the tomato (*Lycopersicon esculentum*). As seen from the morphologies illustrated in Figure 7, valerian (*Valeriana officinalis*) and cucumber (*Cucumis anguria* L.) seeds show an almond-shaped structure, while dill (*Anethum graveolens*) demonstrates a flat oval-shaped structure. On the other hand, coriander (*Coriandrum sativum*) and tomato (*Lycopersicon esculentum*) seeds indicate a smooth spherical-shaped structure and a fluffy ball-shaped appearance, respectively. Moreover, parsley (*Petroselinum hortense*) and cress (*Lepidium sativum* L.) seeds exhibit a saddle-shaped structure, while basil (*Ocimum basilicum*) and rocket (*Eruca sativa*) show a tuber-shaped structure and a bean-shaped structure, respectively. The above-mentioned differences can be ascribed to phytomorphological properties and phytochemical compositions of the plant seeds [42–51].

3.3. Plant growth tests

In the present agricultural study, the medicinal plants sprouted for about 5–7 days, and the visual observations indicated that the plants in the MAP pots had a higher growth rate than those in the control pots. It is recorded that all studied plants grew at various rates depending on their species (Figure 8a–f). The results of the greenhouse experiments demonstrated that rates of increase in total fresh weights, total dry weights, and fresh heights of the harvested medicinal plants grown in soil amended with the struvite (recovered at the previous optimum conditions) were (a) 67%, 52%, and 12% for valerian (*Valeriana officinalis*); 121%, 75%, and 18% for



Figure 9. Growth status of medicinal at application rate of 2.5 g struvite/kg soil after 25 days growth (control pots at left-hand side and MAP pots at right-hand side): (a) Valerian (*Valeriana officinalis*); (b) Cucumber (*Cucumis anguria* L.); (c) Dill (*Anethum graveolens*); (d) Coriander (*Coriandrum sativum*); (e) Tomato (*Lycopersicon esculentum*); (f) Parsley (*Petroselinum hortense*); (g) Basil (*Ocimum basilicum*); (h) Rocket (*Eruca sativa*); (i) Cress (*Lepidium sativum* L.).

cucumber (*Cucumis anguria* L.); (b) 421%, 260%, and 47% for dill (*Anethum graveolens*); (c) 314%, 318%, and 27% for coriander (*Coriandrum sativum*); (d) 432%, 566%, and 30% for tomato (*Lycopersicon esculentum*); (e) 285%, 683%, and 26% for parsley (*Petroselinum hortense*); (f) 200%, 225%, and 9% for basil (*Ocimum basilicum*); (g) 857%, 656%, and 92% for rocket (*Eruca sativa*); and (h) 146%, 115%, and 28% for cress (*Lepidium sativum* L.), respectively, compared to the corresponding control pots. Based on the total fresh-dry weights and fresh height measurements of harvested plants, the results clearly showed that the plants cultivated in soil, which was amended with the struvite, grew better than the control groups of no fertilizer (Figure 9). According to overall results, rocket (*Eruca sativa*) cultivated in soil amended with the struvite showed the best activity in terms of all growth parameters.

For the present case, *F* (variance ratio) tests showed that there was a statistically significant difference ($F = 3.6035$, $p = 0.0442$) between struvite-fertilized and control pots in terms of total fresh weights (data set of fresh weight measurements obtained from each harvested medicinal plant). Likewise, the same parametric test concluded that there was a sufficient evidence for a significant difference ($F = 3.6324$, $p = 0.0433$) between the paired groups in terms of dry weights (data set of dry weight values obtained after drying of each harvested medicinal plant at 105 °C for 24 h). For both cases, the null hypothesis (H_0: there is not a significant difference between groups concerning the variance of samples) was rejected in favour of the alternative hypothesis (H_1), since the *p* values were computed lower than the α level of 0.05 within 95% confidence.

Finally, fresh height values obtained for the five tallest plant individuals of each plant species were appraised using appropriate statistical tests, and the differences between control and MAP sets were evaluated. As seen from results summarized in Table 1, there were no

Table 1. Statistical comparison of fresh sprout heights for MAP-amended pots (M) and control pots (C) within 95% confidence limits ($\alpha = 0.05$).

Paired groups	Shapiro–Wilk *W* test (normality / non-normality)	Levene's (W50) test (variance homogeneity)	Parametric / non-parametric tests	Descriptive statistics
Valerian (*Valeriana officinalis*)	C: $p = 0.8082$ (Normal) M: $p = 0.5646$ (Normal)	$F = 0.1610$ $p = 0.6987$ (Homogeneous)	Unpaired *t*-test	$se_p = 1.511$ $t = 1.6547$ $p = 0.1366$ PW = 53.48%
Cucumber (*Cucumis anguria* L.)	C: $p = 0.3528$ (Normal) M: $p = 0.8658$ (Normal)	$F = 0.6054$ $p = 0.4589$ (Homogeneous)	Unpaired *t*-test	$se_p = 1.1198$ $t = 2.8219$ **$p = 0.0224$** PW = 93.9%
Dill (*Anethum graveolens*)	C: $p = 0.4851$ (Normal) M: $p = 0.2407$ (Normal)	$F = 1.8367$ $p = 0.2124$ (Homogeneous)	Unpaired *t*-test	$se_p = 1.9917$ $t = 2.2493$ $p = 0.0546$ PW = 80.02%
Coriander (*Coriandrum sativum*)	C: **$p = 0.0284$** (Non-normal) M: $p = 0.5837$ (Normal)	No need to check variance homogeneity	Non-parametric test	**$p_{MW} = 0.0159$** **$p_{KW} = 0.0163$**
Tomato (*Lycopersicon esculentum*)	C: $p = 0.9015$ (Normal) M: $p = 0.6527$ (Normal)	$F = 0.1969$ $p = 0.6690$ (Homogeneous)	Unpaired *t*-test	$se_p = 0.7572$ $t = 3.9354$ **$p = 0.0043$** PW = 99.74%
Parsley (*Petroselinum hortense*)	C: $p = 0.6682$ (Normal) M: $p = 0.1589$ (Normal)	$F = 0.8494$ $p = 0.3837$ (Homogeneous)	Unpaired *t*-test	$se_p = 0.6293$ $t = 4.2270$ **$p = 0.0029$** PW = 99.9%
Basil (*Ocimum basilicum*)	C: $p = 0.5563$ (Normal) M: $p = 0.8327$ (Normal)	$F = 0.1216$ $p = 0.7363$ (Homogeneous)	Unpaired *t*-test	$se_p = 0.3124$ $t = 1.7285$ $p = 0.1222$ PW = 57.21%
Rocket (*Eruca sativa*)	C: **$p = 0.0415$** (Non-normal) M: $p = 0.1105$ (Normal)	No need to check variance homogeneity	Non-parametric test	**$p_{MW} = 0.0159$** **$p_{KW} = 0.0163$**
Cress (*Lepidium sativum* L.)	C: $p = 0.8764$ (Normal) M: $p = 0.5029$ (Normal)	$F = 0.0167$ $p = 0.9005$ (Homogeneous)	Unpaired *t*-test	$se_p = 0.4377$ $t = 3.2898$ **$p = 0.0110$** PW = 98.18%

statistically significant differences ($p > \alpha = 0.05$) between MAP-amended and control groups of valerian (*Valeriana officinalis*) ($p = 0.1366$), dill (*Anethum graveolens*) ($p = 0.0546$), and basil (*Ocimum basilicum*) ($p = 0.1222$) in terms of fresh heights, while significant differences ($p < \alpha = 0.05$) were recorded between the paired groups (struvite-fertilized and control set) of cucumber (*Cucumis anguria l.*) ($p = 0.0224$), coriander (*Coriandrum sativum*) ($p_{MW} = 0.0159$ and $p_{KW} = 0.0163$), tomato (*Lycopersicon esculentum*) ($p = 0.0043$), parsley (*Petroselinum hortense*) ($p = 0.0029$), rocket (*Eruca sativa*) ($p = 0.0159$), and cress (*Lepidium sativum l.*) ($p_{MW} = 0.0159$ and $p_{KW} = 0.0163$) in terms of the measured fresh heights.

It is noted that Mg deficiency in the soil causes a decrease in P uptake, and thus the plant does not make use of P available in the soil as much as necessary. From this point of view, struvite application is regarded to be attractive and beneficial in soils and crops which need high Mg and P [35]. Utilization of struvite increases P uptake since Mg is present in it. In this regard, it has a synergistic effect on P absorption [54]. According to this incentive-stimulation phenomenon between Mg and P, higher yields obtained in fresh-dry weights and height parameters for the relevant medicinal plant species was probably ascribed to higher Mg content and the synergistic effect of Mg on P uptake due to struvite application [55]. The foregoing results revealed that although a synergistic effect on both weight and height parameters for some plant species (herein cucumber, coriander, tomato, parsley, rocket, and cress), the fertility value of struvite was more effective on fresh-dry weights than fresh heights for some plant species (herein valerian, dill, and basil). The different responses of plants to MAP dosing (i.e. improvement in both weight and height parameters or only considerable improvement in weight parameter compared to height parameter) may be attributed to (i) daily uptake/absorption (of nutrients, secondary nutrients, and trace elements in the soil) due to distinct growth characteristics [42–51] of the relevant species, and (ii) their adaptability to other external factors (e.g. light intensity/spectrum, pH level of the growing medium, surrounding temperature, growing medium temperature) due to dissimilar plant metabolism.

3.3. Fire-retardant properties of the recovered struvite

To interpret the results of the flammability test in a numerical manner, the photographs of the burning wood plates

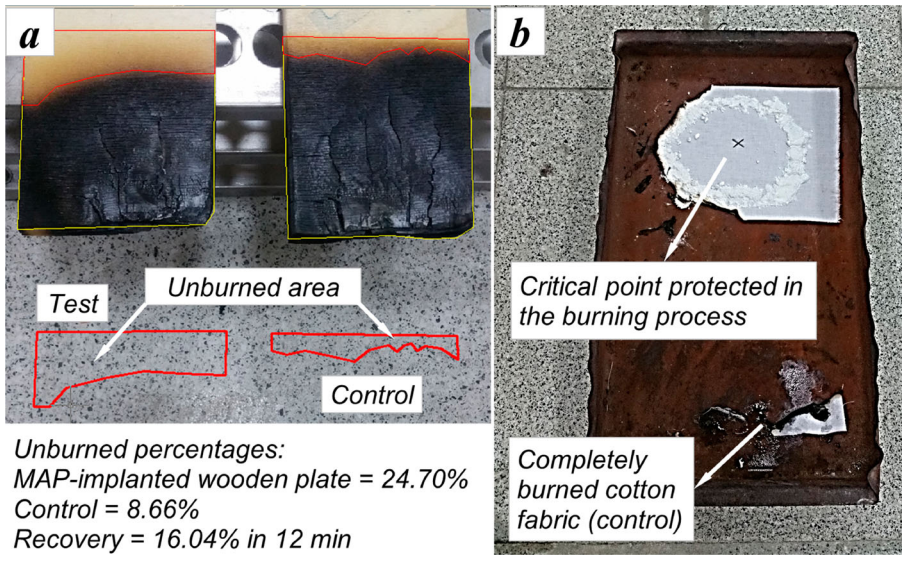


Figure 10. Photographs showing burned forms of the materials exposed to the flammability test: (a) Wooden plates (struvite-implanted at left-hand side and control at right-hand side); (b) Cotton fabric specimens.

were transferred to AutoCAD® 2004 (Autodesk Inc., San Rafael, CA) software using 'Raster Image' option and the areas of burned parts were calculated, and then burned and unburned percentages were determined accordingly. According to the results obtained on the burned parts, the burning percentage of the struvite-implanted wooden plate was 75.3%, while the burning percentage of the unmodified wooden panel (control panel) was 91.34%. In other words, the percentage of struvite-added wooden plate remaining unburned during the test period was 24.7%, while the percentage of unburned control panel during the test period was determined as 8.66% (Figure 10a). The results obtained after a 12-min slow burning process demonstrated that the struvite implantation into a wooden plate contributed to the recovery of a wooden area of 16.04%. According to digitization on the computer-aided environment, the struvite-implanted wooden plate burned over an average length of 7.72 cm during the 12-min burning, while the control plate burned over an average length of 9.37 cm within the same duration. According to these values, for a 12-min test period, the average flame rates were determined as 0.64 and 0.78 cm/min for the struvite-added wooden panel and the control panel, respectively. This indicated that the flame rate in the control plate was 21.88% greater compared to the test plate, or in other words, the flame rate was retarded about 22% by the struvite implantation.

For the second part of the flammability study, it was visually observed that the control fabric completely burned within about 2 min, and the marked centre disappeared. On the other hand, for the test fabric, the sprinkled struvite decreased spread rate and intensity of the flame, and then completely extinguished it in a burning time of about 1.5 min (Figure 10b). Results showed that the marked centre simulating a critical point on the test fabric was protected in a burning event with the help of a circular struvite barrier. Overall, results of the flammability tests concluded that the dried and crumbled/implanted form of struvite used as a fire-retardant barrier demonstrated a remarkable flame-resistant behaviour for both wooden plate and cotton fabric. Besides its fertilizing potential, it is believed that utilization of struvite as a sustainable, cost-effective, and eco-friendly [12,29] fire-retardant material will contribute to its universal attractiveness particularly for fire management activities in rural regions.

3.4. Assessment of literature findings on the fertilizer value of struvite for potted plants

Performance data regarding the fertilizing effect of struvite on cultivating different types of potted plants (e.g. Chinese flowering cabbage, Chinese chard, water spinach, water convolvulus, broad bean, purslane, garden cress, grass, garden rocket, dill, fennel, parsley, maize, tomato, lettuce, pepper, valerian, cucumber, coriander, basil) are presented in Table 2.

The data shown in Table 2 indicate that struvite dosage (2.5 g struvite/kg soil) applied in the present experimental study seems to be in line with those implemented for other types of wastewaters such as anaerobically pretreated poultry manure wastewater (2.63 g struvite/kg garden soil) [14], baker's yeast industry anaerobic effluent (2.86 g struvite/kg garden soil) [34], and swine wastewater (2.4 g struvite/kg garden soil) [16]. On the other hand, the present recovery

Table 2. Fertilizing effect of struvite deposit on cultivating different types of plants.

Type of wastewater (initial NH_4^+—N concentration)	Operating conditions for struvite synthesis	Stuvite dosage	Plant type (cultivation period)[a]	Fertility assessment (struvite pots)	Reference
Landfill leachate (2750–2900 mg/L)	$MgCl_2{\cdot}6H_2O + Na_2HPO_4.12H_2O$ Mg:N:P = 1:1:1 pH = 9.0 Recovery = 92%	1.4 g struvite/kg soil (with 1×, 2×, 4×, 8× MAP)	Chinese flowering cabbage, Chinese chard, water spinach, water convolvulus (35 days)	Growth rate was greater than 5 mm/day or about 15 mg/day (for 8× MAP)	[35]
Synthetic industrial wastewater (2651.5 mg/L)	Bittern + K_2HPO_4 Mg:N:P = 1.6:0.6:1 pH = 9.6 Recovery = Not reported	At a rate of 2% prior to sowing by mixing it with soil	Broad bean (15, 30, 45 days)	After 45 days the rate of increase in fresh and dry weight reached 191.2 and 248% for struvite as compared with control.	[56]
Up-flow anaerobic sludge blanket pretreated poultry manure wastewater (1318 ± 7 0 mg/L)	$MgCl_2{\cdot}6H_2O + K_2HPO_4$ Mg:N:P = 1:1:1 pH = 9.0 Recovery = 85.4%	(218 mg + 3 g MAP) / (1.14 kg garden soil or 1.14 kg sand)	Purslane, garden cress, grass (11 days)	28–257%; 60–402%; 18–156% (ranges of increases in fresh-dry weights and fresh heights for all plants)	[2]
		1.2 g struvite/0.45 kg soil	Garden rocket, dill, fennel, parsley (15 days)	405, 488, 51%; 154, 191, 44%; 152, 379, 27%; 141, 208, 22% (increases in fresh-dry weights and fresh heights, respectively)	[14]
Raw semiconductor wastewater (80–250 mg/L)	$MgCl_2{\cdot}6H_2O$ + NaOH Mg:N:P = 1:1:1 pH = 9.0 Recovery = 89%	1.6 g struvite/kg soil	Chinese cabbage (45 days)	The heaviest wet and dry weight was found to be 5373 and 573 mg at 1.6 g struvite/kg soil.	[57]
Baker's yeast industry anaerobic effluent (528.8 ± 15.6 mg/L)	$MgCl_2{\cdot}6H_2O + H_3PO_4$ (85%) Mg:N:P = 1.5:1:1 pH = 9.0 Recovery = 92.3%	2.86, 5.71, 8.58, 11.43 g struvite/kg soil	Maize, tomato (54 days)	N, P, and Mg uptakes of plants were significantly higher at struvite 2×, 3×, and 4× dosages compared with NPK application.	[34]
Swine wastewater (628–1061 mg/L)	$MgCl_2{\cdot}6H_2O + K_2HPO_4$ Mg:N:P = 1:1:1 pH = 9.0 Recovery = 81%	0.4, 0.8, 1.2, 2.0 and 2.4 g struvite/kg soil	Lettuce (63 days)	7117 (±367) T-N, 313 (±16) P_2O_5, 105 (±7) Mg mg/kg dry vegetable were obtained for the harvested leaves.	[16]
Biocatalytic calcification reactor effluent (270 ± 28.43 mg/L)	$MgCl_2{\cdot}6H_2O + H_3PO_4$ (85%) Mg:N:P = 1.25:1:1 pH = 9.36 Recovery = 96%	0.5, 1, 2.5, 5, 7.5, 10 g struvite/ 200 g raw soil	Pepper (75 days)	Dosages of 5, 7.5, 10 g/200 g grew faster and bloomed earlier than the others.	[58]
Synthetic (simulated) fertilizer wastewater (1000 mg/L)	$MgO + NaH_2PO_4.2H_2O$ Mg:N:P = 1.2:1:1 pH = 9.0 Recovery = 98.7%	2.5 g struvite/kg soil	Valerian, cucumber, dill, coriander, tomato, parsley, basil, rocket, cress (25 days)	67, 52, 12%; 421, 260, 47%; 314, 318, 27%; 432, 566, 30%; 285, 683, 26%; 200, 225, 9%; 857, 656, 92%; 146, 115, 28% (increases in fresh-dry weights and fresh heights, respectively)	Present study

[a]Botanical (scientific) names of the plants can be found in the relevant references.

percentage (98.7%) seems to be higher than those obtained in real wastewaters. However, this may be expected since the synthetic solution medium is much more controlled for a consistent physicochemical treatability process, and industrial/animal wastewaters contain various ions (e.g. Na^+, Ca^{2+}, K^+, and SO_4^{2-}) that can form complex components and undesired impurities [34]. Moreover, the performance data show that excess dosages of Mg^{2+} provide striking benefits (i.e. increases in fresh-dry weights and fresh heights, high uptakes of macro nutrients, fast growing, and early blooming) on cultivation of several types of plant species such as broad bean [56], maize and tomato [34], pepper [58], and the medicinal plants tested in the present study. In this regard, the positive effect of overdose conditions (Mg^{2+}:NH_4^+—N:PO_4^{3-}—P =1.2:1:1) obtained in the present agricultural period was found to be compatible with the findings of other studies [34,56,58].

Overall, the studies reveal that the struvite recovery is feasible with an efficiency between 81% and 98.7% for different types of wastewaters (e.g. landfill leachate, synthetic industrial wastewater, anaerobically pretreated poultry manure wastewater, raw semiconductor wastewater, baker's yeast industry anaerobic effluent, swine wastewater, biocatalytic calcification reactor effluent, synthetic (simulated) fertilizer wastewater, etc.) having an initial ammonium concentration from 80 to 2900 mg/L by applying various chemical combinations and Mg:N:P molar ratios. Moreover, various doses ranging from 0.4 to 11.43 g MAP/kg soil have been applied to evaluate the struvite's slow-release fertilizing potential in the growth of different plants (e.g. medicinal herbs, vegetables) for cultivation periods varying from 11 to 75 days.

It is evident from previous studies that plants cultivated in struvite-amended soils have been reported to yield significantly higher growth rates and nutrient uptakes in comparison with values obtained for control pots. In some studies [34,58], it has been reported that N, P, and Mg uptakes of plants cultivated at higher struvite doses were significantly higher, and they grew faster and bloomed earlier than the others. Additionally, some studies [5,35] have demonstrated that overdosing of 2–10 times of struvite in the soil did not cause any problems (i.e. inhibition of sprouting, danger of burning plant roots, etc.) on the growth of plants due to its limited solubility in water. There have been many other studies appraising the effect of struvite as a source of slow-release, high-quality fertilizer on variety of crop species [2,5,13,16,33–35,57,59–61]. Moreover, a detailed discussion on different aspects of struvite recovery processes including the use of seed material, alternative Mg sources, nitrogen preservation, and fertilizer value, can be found in the comprehensive review elaborated by Kataki et al. [55].

As seen from the above-noted discussion, there is a broad variation in fertilizing value of struvite on the cultivation of potted plants. Possible distinctions in the previous findings are related to several factors such as struvite source, soil/growing medium type, crop type, dose and type of used chemicals, cultivation period, and initial pollutant concentration. However, considering the associated advantages of struvite precipitation/recovery (i.e. reduction of nutrient load on the subsequent treatment units, transformation of excess nutrients into a non-polluting compound, production of an excellent slow-release and multi-nutrient fertilizer in cultivating crops, reduction of sludge volume compared to other technologies, and potential to produce an alternative raw material for different industrial sectors, etc.), this process appears to be an attractive and feasible alternative to commercial chemical fertilizers.

4. Conclusions

In the present study, struvite (magnesium ammonium phosphate hexahydrate, $MgNH_4PO_4{\cdot}6H_2O$, MAP) recovered from high-strength ammonium-containing simulated wastewater was utilized as a slow-release fertilizer in cultivation of nine medicinal plants, and as a fire-retardant barrier for both wooden plate and cotton fabric. The fertilizing value of struvite was assessed by a set of greenhouse experiment and its flame-retardant potential was explored by performing flammability tests. Based on the experimental findings, conclusions obtained within the framework of this study and recommendations for required future research were summarized as follows:

(1) The SEM micrographs of the struvite crystals showed irregular-shaped crystals with various sizes, and the most common morphology of grown crystals observed in the sample micrograph was the hexagonal prism shaped.
(2) Under the operating conditions for struvite synthesis ($MgO + NaH_2PO_4{\cdot}2H_2O$, Mg^{2+}:NH_4^+—N:PO_4^{3-}—P = 1.2:1:1, pH = 9.0, total mixing time = 15 min, initial NH_4^+—N = 1000 mg/L, NH_4^+—N recovery = 98.7% of NH_4^+—N), the EDS results indicated that MAP precipitate consisted of 4% N, 23.2% Mg, 27.6% P, and its BET surface area was 16.35 m^2/g.
(3) TGA and DTG curves showed that struvite precipitate lost only 29% of its weight during the combustion process reaching up to 900°C, and the thermogravimetric curves (TGA, DTG, and DSC) clearly confirmed the fire-retardant property of struvite. Also, the FTIR

spectrum corroborated the existence of water of hydration, N–H and P–O bonds, and NH_4^+ and PO_4^{3-} ions associated with the magnesium ammonium phosphate hexahydrate.

(4) Parametric/non-parametric statistical analyses corroborated that the fertility value of struvite (MAP) showed a synergistic effect on both weight and height parameters in six of medicinal plants (e.g. cucumber (*Cucumis anguria* L.), coriander (*Coriandrum sativum*), tomato (*Lycopersicon esculentum*), parsley (*Petroselinum hortense*), rocket (*Eruca sativa*), and cress (*Lepidium sativum* L.)) compared to the control pots of no fertilizer. On the other hand, MAP dosing was found to be more effective on fresh-dry weights than fresh heights in three of plant species (i.e. valerian (*Valeriana officinalis*), dill (*Anethum graveolens*), and basil (*Ocimum basilicum*)) due to different growth properties and plant metabolisms.

(5) For a 25-day cultivation period and a struvite dosage of 2.5 g struvite/kg soil, the rocket grown in struvite-amended soil was observed as the best-fertilized plant with increases of 857%, 656%, and 92%, respectively, in total fresh weight, total dry weight, and fresh sprout height.

(6) Dried and crumbled/implanted form of struvite applied as a fire-retardant barrier showed a satisfactory flame-resistant behaviour for both wooden plate and cotton fabric. For a 12-min slow burning process, struvite implantation into a wooden plate contributed to a 16.04% of recovery in a wooden area and provided about 22% of retardation in the flame spread rate.

(7) For the purpose of extending the obtained agricultural database, further research should be conducted based on a larger scale (starting with pilot-scale applications) and a longer cultivation period to explore the ameliorative effect of struvite dosing on the growth of different plants.

(8) Within the framework of further investigations, a series of physicochemical treatability tests and optimization studies on different real wastewaters will be carried out. Additionally, the physical and the chemical properties of the final product to be obtained in the form of struvite will be examined in detail to express the interest in its using as an alternative raw material in other industrial processes.

(9) In the later stages, the potential of the thoroughly characterized struvite to be used as a beneficial and economic absorbent in the elimination of different types of contaminants will be investigated within the scope of isotherm and kinetic-based modelling studies. Additionally, the usability of struvite as a cement-binding material will be explored by performing a set of mechanical strength tests for the aim of integrating this product in the construction sector. The aspects mentioned in items 7, 8, and 9 are beyond the scope of the present study, and they have been left for future investigations to provide new insights.

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