

Review Article

An evaluation of nutrient recycling from livestock and poultry waste using struvite-enriched compost - A review

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ABSTRACT

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The rapid expansion of livestock and poultry production has resulted in the generation of large quantities of organic waste, posing significant environmental challenges. Improper disposal leads to nutrient loss, eutrophication, greenhouse gas emissions, and public health concerns. Nutrient recovery from these wastes has emerged as a sustainable strategy within the framework of circular bioeconomy. Among various approaches, struvite ($MgNH_4PO_4 \cdot 6H_2O$) precipitation integrated with composting has gained increasing attention due to its ability to recover nitrogen (N) and phosphorus (P) efficiently while improving compost quality. This review critically evaluates the mechanisms of struvite formation, integration with composting processes, agronomic benefits, environmental impacts, and economic feasibility. The findings suggest that struvite-enriched compost significantly reduces nutrient loss, enhances fertilizer efficiency, and offers a promising pathway for sustainable waste management. However, challenges related to cost, scalability, and process optimization remain. Future research should focus on field validation, life cycle assessment, and policy support to facilitate large-scale adoption.



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INTRODUCTION

Composting is the controlled aerobic biological decomposition of organic matter into stable, humus like product called compost. The composting process is carried out by a diverse population of predominantly aerobic micro-organisms that decompose organic material in order to grow and reproduce. The activity of these micro-organisms is encouraged through management of the carbon-to nitrogen (C:N) ratio, oxygen supply, moisture content, temperature, and pH of the compost pile (Alam *et al.*, 2013; Liu *et al.*, 2011; Rana *et al.*, 2020; Roy *et al.*, 2013; Won *et al.*, 2016). The global expansion of livestock and poultry production has led to a substantial increase in the generation of organic wastes, particularly manure and litter. These wastes are inherently rich in essential plant nutrients, including nitrogen

(N), phosphorus (P), and potassium (K), along with organic matter that can improve soil health. However, inefficient management practices often result in significant nutrient losses through volatilization, leaching, and runoff, contributing to environmental problems such as eutrophication, soil degradation, and greenhouse gas emissions (Chadwick *et al.*, 2011; Sharpley *et al.*, 2013). Composting has long been recognized as an effective and sustainable method for stabilizing livestock and poultry wastes. Through controlled aerobic decomposition, composting converts raw organic materials into a more stable, pathogen-reduced, and humus-like product suitable for soil application (Bernal *et al.*, 2009; Rahman *et al.*, 1997). The resulting compost improves soil structure, enhances microbial activity, and contributes to long-term soil

fertility. Despite these advantages, conventional composting systems suffer from substantial nutrient losses, particularly nitrogen, which is often volatilized as ammonia (NH₃) during the thermophilic phase. Phosphorus, although less volatile, may become immobilized or lost through leaching, thereby reducing the agronomic value of the final compost product (Sánchez-Monedero *et al.*, 2001).

In recent years, increasing attention has been directed toward improving nutrient conservation during composting, leading to the development of enhanced composting strategies such as the incorporation of mineral additives and nutrient recovery technologies. Among these, the integration of struvite precipitation into waste management systems has emerged as a promising approach. Struvite (magnesium ammonium phosphate hexahydrate; MgNH₄PO₄·6H₂O) is a crystalline compound formed through the reaction of magnesium (Mg²⁺), ammonium (NH₄⁺), and phosphate (PO₄³⁻) ions under alkaline conditions. It serves as a slow-release fertilizer containing essential nutrients in plant-available forms (Le Corre *et al.*, 2009). The recovery of struvite from livestock and poultry waste streams is particularly important in the context of global phosphorus scarcity and the increasing demand for sustainable fertilizer alternatives. Phosphorus is a finite resource, primarily obtained from phosphate rock, and its inefficient use in agriculture has raised concerns about long-term food security (Rahman *et al.*, 2011 and 2014). At the same time, excess phosphorus discharge from agricultural systems contributes significantly to water pollution. Struvite recovery offers a dual benefit by simultaneously mitigating environmental risks and recycling valuable nutrients into a reusable form (Doyle and Parsons, 2002).

In this context, the present review aims to critically assess nutrient recycling from livestock and poultry waste through struvite-enriched compost (Modak *et al.*, 2019; Sarker *et al.*, 2009). The review focuses on the mechanisms of struvite formation, integration with composting processes, agronomic performance, environmental benefits, and challenges associated with large-scale implementation.

Methodology for struvite accumulation in composting systems

Overview of Approach

Struvite accumulation in compost can be achieved through two principal strategies: (i) in-situ formation, where struvite crystallizes directly within the composting matrix, and (ii) ex-situ recovery followed by enrichment, where struvite is first precipitated from liquid waste streams and subsequently incorporated into compost. Both approaches aim to enhance nutrient retention, particularly nitrogen (N) and phosphorus (P), while improving the agronomic value of the final compost product (Lee *et al.*, 2009).

Raw materials and pre-treatment

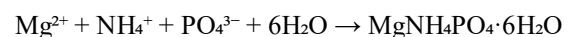
Livestock and poultry wastes (e.g., cattle manure, broiler and layer manure) are collected and subjected to pre-treatment to ensure process efficiency. Cattle and buffalo manure, sheep and goat manure, poultry manure (broiler and layer), Horse manure, pig manure, pet animal waste, slaughterhouse waste

(rumen ingesta), wasted feeds, hatchery waste, tannery waste, dead animals, MSW, tree leaves and agricultural crop residues, fruit & vegetable wastes, fish wastes, food processing wastes (Ahsan *et al.*, 2013; Haque *et al.*, 2021; Mustafa *et al.*, 2026; Sarker *et al.*, 2018). Pre-treatment typically includes: i. Removal of large debris through screening, ii. Size reduction to improve microbial accessibility, iii. Adjustment of moisture content to 50–65% and iv. Separation of liquid fraction (for ex-situ struvite recovery). The liquid fraction (manure slurry or digestate) is particularly important as it contains high concentrations of soluble ammonium (NH₄⁺) and phosphate (PO₄³⁻), which are essential precursors for struvite formation. Efficient struvite precipitation requires optimization of physicochemical conditions. The pH is adjusted to an alkaline range (typically 8.0–9.5) using alkaline agents such as Sodium hydroxide (NaOH) or Calcium hydroxide (Ca(OH)₂)

Magnesium Supplementation

Since livestock waste is often deficient in magnesium therefore, an external Mg source is added through magnesium chloride (MgCl₂·6H₂O), Magnesium oxide (MgO) or Magnesium sulfate (MgSO₄). The molar ratio of Mg:N:P is maintained close to 1:1:1, although slight excess Mg (e.g., 1.1–1.3) is often applied to ensure complete precipitation (Bashan and Bashan, 2004; Much and barr, 2001).

Struvite formation occurs via a crystallization reaction:



Supersaturation is induced to promote nucleation and crystal growth. The formed struvite crystals are then separated via sedimentation or filtration. After crystallization the struvite crystals are separated using settling tanks, centrifuges, or filters. The crystals may be washed and dried to improve purity and the treated effluent (with reduced nutrient load) can be reused or safely discharged. Struvite typically contains 5–6% N, 12–13% P (as P₂O₅) and 9–10% Mg.

Recovered struvite is mixed with composting materials and the mixing ratio is 1–5% (w/w) depending on nutrient requirements. Combined with bulking agents (e.g., straw, sawdust) to maintain proper C/N ratio (20–30:1). Alternatively, Mg salts are directly added to compost piles. Promotes struvite formation within the compost matrix and reduces ammonia volatilization during thermophilic phase of composting. The composting process is carried out under controlled aerobic conditions such as Temperature might be 55–65°C (thermophilic phase), composting period approximately 30–60 days (Lee *et al.*, 2009). Regular turning or forced aeration needed to ensure oxygen for aerobic microorganisms for composting. Initial moisture content maintained at 60–65%. The presence of struvite stabilizes ammonium, thereby reducing nitrogen loss and enhancing nutrient retention.

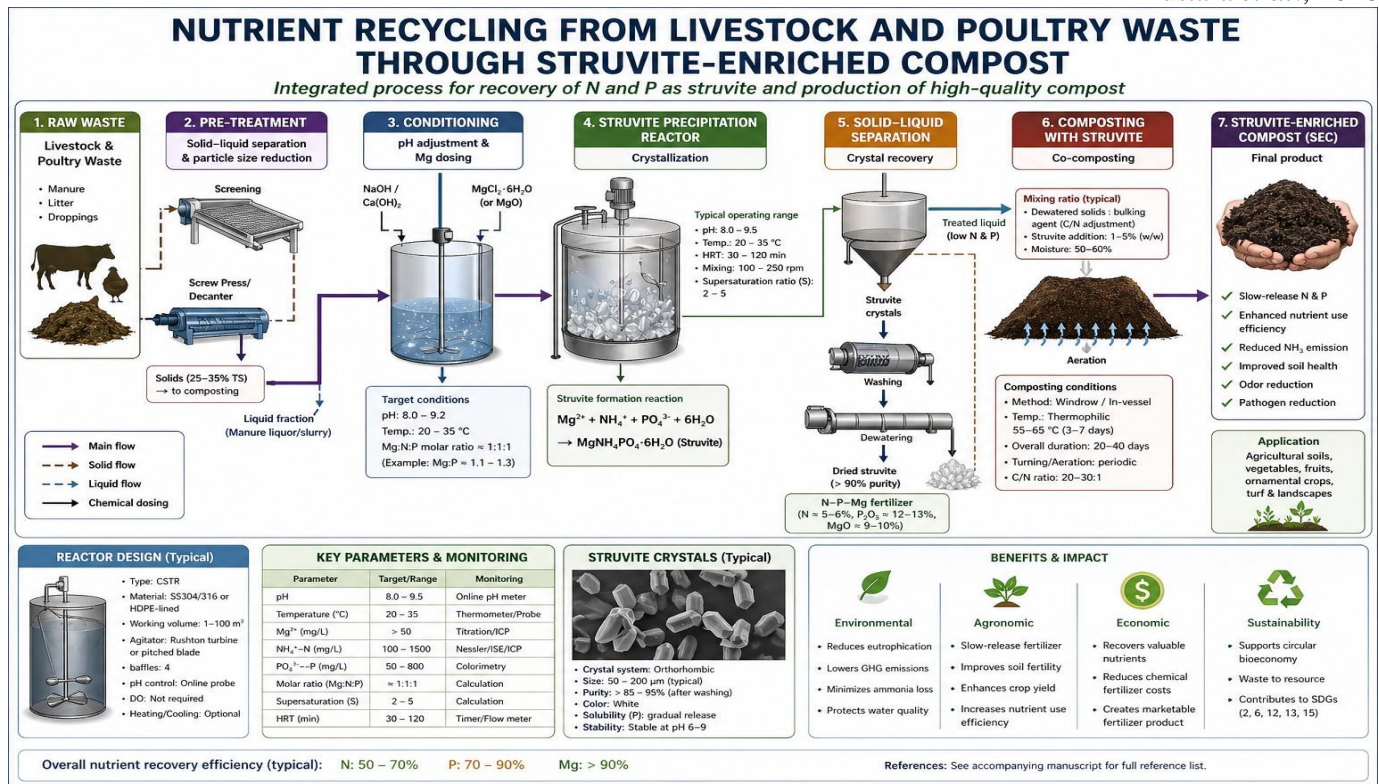


Figure 1: Flowchart of Struvite enriched compost production Formation and nutrient recycling

Essentials of struvite recovery

It has been estimated that global reserves of mined phosphate rock amount to approximately 7,000 million tons as P₂O₅, of which about 40 million tons are extracted annually for fertilizer production and human consumption (Florida Institute of Phosphate Research, 2005). The global demand for phosphorus is projected to rise by around 1.5% per year. At this rate, available phosphate rock reserves may become depleted within roughly 90 years. [Shu et al. \(2006\)](#) further projected that, under a continuous 1.5% increase in consumption, phosphate rock reserves could be exhausted by around 2090. Conversely, if usage decreases by 1.5% annually, reserves might last until approximately 2200. However, such a reduction in phosphorus use is unlikely without recovering phosphorus from alternative sources, particularly organic and waste-derived phosphorus, as modern agriculture heavily depends on phosphorus inputs and no true substitute currently exists ([Sharpley, 2001](#)).

Currently, the global average application rate of phosphorus fertilizer is about 21.62 kg ha⁻¹ yr⁻¹ (as P₂O₅) across 1.48 billion hectares of arable land ([Rahman et al., 2014](#)). This level is already below the estimated requirement of 40 kg ha⁻¹ yr⁻¹, indicating an emerging supply constraint. If phosphorus reserves become exhausted, application rates could drop drastically to nearly 1 kg ha⁻¹ yr⁻¹, depending on population demand ([Shu et al., 2006](#)). Such a reduction would severely threaten global food production and the ability to feed a growing population, making phosphorus recovery from organic and waste sources an urgent necessity. In this context, wastewater phosphorus recovery represents a key sustainable solution.

The production of 1 kg of magnesium ammonium phosphate (MAP) per day is sufficient to fertilize approximately 2.6 hectares of farmland at an application rate of 40 kg P ha⁻¹ yr⁻¹ (as P₂O₅), potentially contributing to an additional grain yield of about 9 tons, European Fertilizer Manufacturers

Association, 2000). It has been estimated that a wastewater treatment plant (WWTP) can recover about 1 kg of MAP from every 100 m³ of wastewater, assuming a phosphate concentration of 7 mg PO₄³⁻/L and a phosphorus recovery efficiency of 55.3% ([Munch and Barr, 2001](#)). On a global scale, if 50% of the world population (approximately 6 billion people) were connected to WWTPs, around 0.63 million tons of phosphorus per year could be recovered as P₂O₅, assuming each person contributes about 2.5 g of phosphorus annually and a recovery efficiency of 55% ([Shu et al., 2006](#)). Furthermore, if full global coverage and 100% recovery efficiency were achieved, phosphorus recovery could potentially increase by 3.6 times. It is also important to extend phosphorus recovery efforts to livestock wastewater streams. Overall, MAP crystallization offers a dual benefit: it produces a slow-release, high-quality fertilizer for agricultural use while simultaneously mitigating environmental pollution by recovering nitrogen and phosphorus from waste streams.

Struvite enriched compost and soil fertility along with nutrient recycling

When integrated with composting, struvite plays a critical role in enhancing nutrient retention and improving compost quality. The formation or addition of struvite during composting helps to stabilize ammonia nitrogen, thereby reducing ammonia emissions and preserving nitrogen within the compost matrix ([Figure 1](#)). Furthermore, the presence of struvite increases phosphorus availability in the final product, transforming compost into a more balanced and efficient fertilizer. This combined product, often referred to as struvite-enriched compost, represents an advanced nutrient management strategy that aligns with the principles of circular bioeconomy and sustainable agriculture ([Massey et al., 2009](#); [Yetilmezsoy et al., 2009](#)). From a practical standpoint, the application of struvite-enriched compost has demonstrated significant agronomic benefits. As it contains slow-release fertilizer, it provides a steady supply of

nutrients, reducing the risk of nutrient leaching and improving nutrient use efficiency and it is far better than fresh manure and normal compost (Table 1). This is particularly beneficial for crops with prolonged growth cycles, where sustained nutrient availability is critical. Additionally, the organic matter in compost enhances soil physical properties, such as aggregation, porosity, and water-holding capacity, while also stimulating beneficial microbial activity (Degryse *et al.*, 2017).

Table 1: Characteristics of raw manure, compost and struvite enriched compost

Parameter	Raw Manure	Compost	Struvite-Enriched Compost
N loss	High	Medium	Low
P availability	Low	Medium	High
Odor	High	Reduced	Low
Environmental risk	High	Medium	Low
Fertilizer efficiency	Low	Moderate	High

Field and pot studies have reported improved plant growth, higher crop yields, and enhanced nutrient uptake when struvite-enriched compost is applied compared to conventional compost or chemical fertilizers alone. Moreover, the gradual release of phosphorus from struvite minimizes fixation in the soil, making it more accessible to plants over time (Agbede, 2025; Talboys *et al.*, 2016). The integration of this technology is particularly relevant for developing countries, where access to chemical fertilizers is limited and organic waste resources are abundant. Despite its promising potential, the adoption of struvite-enriched composting systems remains limited due to technical, economic, and operational challenges (Rahman *et al.*, 2013). These include the cost of magnesium sources, the need for process optimization, and limited awareness among stakeholders. Therefore, a comprehensive evaluation of this integrated approach is essential to identify its strengths, limitations, and future prospects.

Eco-friendly maize and other fodder production

Agricultural soils contribute a relatively small proportion (about 1%) of global CO₂ emissions, whereas methane (CH₄) and nitrous oxide (N₂O) emissions from these systems account for approximately 39% and 60%, respectively (OECD, 2000). Among various agricultural inputs, nitrogen fertilization is recognized as the primary source of soil emissions of nitric oxide (NO), nitrous oxide (N₂O), and methane (CH₄) (Matson *et al.*, 1998). These greenhouse gases—including CO₂, CH₄, NO, and N₂O—play a major role in global warming, prompting ongoing efforts to mitigate their release. Urea is the most widely used nitrogen fertilizer globally; however, it releases nitrogen rapidly into the soil, of which only about 40% is utilized by plants, while the remaining 60% is lost through various pathways (Liang *et al.*, 2007). A significant portion of this loss (26.5–29.4%) occurs through volatilization, which contributes directly to greenhouse gas emissions. Methane has a global warming potential approximately 20 times greater than that of CO₂ in terms of heat trapping capacity (Getachew *et al.*, 2005), while nitrous oxide is about 300 times more effective than CO₂ in absorbing terrestrial infrared radiation in the troposphere (IPCC, 2001), thereby intensifying global warming effects.

The production and use of magnesium ammonium phosphate (MAP) help reduce both phosphorus and nitrogen concentrations in wastewater, thereby lowering the risk of eutrophication in aquatic ecosystems. Due to its slow-release properties (Nelson, 2000), MAP enables more efficient nitrogen uptake by plants with minimal losses following soil application (Lee *et al.*, 2009). Controlled-release nitrogen fertilizers are considered an effective strategy for minimizing N₂O emissions (Chu *et al.*, 2007; Shu *et al.*, 2006). Similarly, Mao *et al.* (2005) reported that slow-release fertilizers are superior alternatives to conventional nitrogen sources because they reduce nitrogen losses through leaching and volatilization. As an efficient slow-release fertilizer, MAP therefore offers a promising approach to environmentally sustainable maize and pakchong fodder production by helping to reduce greenhouse gas emissions and improving nutrient use efficiency (Liu *et al.*, 2011; Rahman *et al.*, 2025).

Recent advances in struvite-enriched compost for plant growth

Recent studies show that struvite (MgNH₄PO₄·6H₂O), particularly when incorporated into compost, is gaining attention as a sustainable slow-release fertilizer for improving crop growth and soil fertility (Rahman *et al.*, 2025). Struvite-enriched compost acts as a dual nutrient source, supplying both nitrogen (N) and phosphorus (P) in a controlled manner while improving overall nutrient recycling efficiency. One major advantage of struvite-based compost is its slow nutrient release pattern, which closely matches plant uptake requirements. This reduces nutrient losses through leaching and volatilization compared to conventional chemical fertilizers. Recent agronomic studies have demonstrated that struvite or struvite-containing amendments can produce plant growth performance comparable to conventional phosphate fertilizers, especially in crops such as maize, wheat, lettuce, and fodder species, while improving nutrient use efficiency and soil nutrient status.

Field and pot experiments have also reported that compost enriched with struvite can significantly enhance biomass production, root development, and phosphorus uptake efficiency, particularly in nutrient-poor soils. The residual effect of struvite in soil further contributes to sustained fertility over multiple cropping cycles, reducing the need for repeated fertilizer applications. In integrated systems, struvite-enriched compost is increasingly being studied as part of circular nutrient management strategies, where nutrients recovered from wastewater are reused in agriculture (Lee *et al.*, 2009; Liu *et al.*, 2011). This approach not only improves crop productivity but also helps reduce environmental pollution by minimizing phosphorus discharge into water bodies, thereby mitigating eutrophication risks.

Recent hydroponic and soilless cultivation studies also highlight that struvite can maintain steady phosphorus availability and support healthy plant growth, although its dissolution rate and nutrient release are influenced by pH, root activity, and environmental conditions. Overall, current evidence suggests that struvite-enriched compost is an effective eco-friendly fertilizer that enhances plant growth, improves nutrient efficiency, and supports sustainable agriculture by linking waste nutrient recovery with crop production systems.

Further scope of struvite-enriched compost

Optimization of production process

There is strong scope for improving the efficiency of struvite incorporation into compost systems by optimizing parameters such as pH, Mg:N:P ratio, aeration, and composting time. Future research can focus on designing low-cost, farmer-friendly reactors or decentralized composting units for rural areas.

Crop-specific fertilizer formulations

Different crops respond differently to nutrient release patterns. Therefore, developing crop-specific struvite-enriched compost formulations (e.g., for maize, rice, vegetables, and fodder crops) can significantly enhance nutrient use efficiency and yield performance.

Long-term soil health and carbon sequestration

More long-term field studies are needed to evaluate how repeated application of struvite-enriched compost effects on soil organic carbon accumulation, microbial community structure, soil phosphorus cycling and overall soil fertility sustainability. This can help position it as a soil regeneration technology, not just a fertilizer.

Integration into circular economy systems

A major future scope lies in integrating struvite recovery and composting into urban wastewater treatment plants, livestock farms, and agro-industrial waste systems. This would create a closed-loop nutrient recycling system, reducing dependence on mined phosphate rock.

Environmental impact assessment

Although it is eco-friendly, more research is needed on the life cycle assessment (LCA) of struvite-enriched compost, greenhouse gas emissions (N₂O, CH₄) under field conditions and reduction of eutrophication potential in water bodies. Such studies will strengthen its environmental validation.

Improvement of nutrient release dynamics

Further scope exists to modify struvite-based compost using biochar, microbial inoculants (PGPR, phosphate solubilizing bacteria) and Nano-mineral additives. These can help fine-tune nutrient release rates and plant availability.

Field-level adoption and socioeconomic feasibility

There is also a need to study farmer acceptance and awareness, cost-benefit analysis compared to chemical fertilizers and policy support for large-scale adoption. This is especially important for countries like Bangladesh where fertilizer subsidy systems already exist.

Use in climate-smart agriculture

Struvite-enriched compost has strong potential in low-emission agriculture systems, particularly for reducing nitrogen loss, phosphorus runoff and fertilizer-related greenhouse gas emissions. Therefore, it can be integrated into climate-smart and regenerative farming models.

CONCLUSION

Struvite-enriched compost is an effective and sustainable approach for recycling nitrogen and phosphorus from livestock and poultry wastes while improving compost

quality and soil fertility. Its slow-release nature enhances nutrient use efficiency, supports crop growth, and reduces nutrient losses such as leaching and volatilization compared to conventional fertilizers. In addition, this technology helps mitigate environmental problems including eutrophication and greenhouse gas emissions, while reducing dependence on non-renewable phosphate rock resources. Although its potential is significant, wider adoption is still limited by cost, process optimization, and lack of large-scale field validation. Struvite-enriched compost represents a promising strategy for sustainable nutrient management within circular bioeconomy and climate-smart agriculture systems.

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Competing Interests

Authors declare no competing interests exist.

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