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Struvite crystallization for nutrient recovery from solid fraction of anaerobic digestate of chicken droppings and food waste

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ABSTRACT

The recovery of nitrogen and phosphorus from anaerobic digestate through struvite crystallization is a sustainable approach for nutrient recycling. However, the effects of hydraulic retention time (HRT) and substrate mixing ratios on struvite recovery from the solid fraction of anaerobic digestate remain insufficiently understood. This study investigated struvite ($MgNH_4PO_4.6H_2O$) crystallization as a nutrient recovery strategy from the solid fraction of anaerobic digestate derived from co-digestion of chicken droppings (CD) and food waste (FW) across three hydraulic retention times (15, 30, and 60 days) and six substrate treatment ratios. Solid-liquid separation of the digestate was done by centrifugation at 2500 rpm for 15 minutes. Solid digestate fractions were characterized and subjected to acid hydrolysis until the pH was 2. Struvite precipitation was conducted at pH 9.0 with a supplementary of 1 M $MgCl_2$ and 1 M KH_2PO_4 in a ratio of 3:2.5 (Mg:P). Recovery efficiencies of both nitrogen (NH_4-N) and phosphorus (PO_4-P) increased significantly with the increase in hydraulic retention time, with the highest values recorded at 60 days in treatment T3 (70% food waste:30% chicken droppings). The maximum recovery efficiencies of nitrogen and phosphorus were 94.4% and 72.8%, respectively. Further, struvite production rates were in the range of 8.31–10.80 g/50 mL acid extract digestate. The study suggests using T3 (70% food waste and 30% chicken droppings) for practical implementation over a 60-day digestion period, demonstrating the viability of the digestates. The use of this method in anaerobic digestion contributes to the principles of the circular economy and sustainable nutrient management.

Keywords: nitrogen, phosphorus, hydraulic retention time, recovery efficiency, digestate management

INTRODUCTION

The global food chain produces several types of organic waste, namely, food waste and livestock manure, which are associated with numerous environmental problems (Schott et al., 2022). Such organic waste streams serve as a source of nitrogen (N) and phosphorus (P); two important macronutrients needed for the sustainable development of agriculture (Ramos et al., 2025). Shortage of phosphorus resources and the increasing cost of synthetic nitrogen fertilizer production makes nutrient recovery from organic waste streams highly attractive (Nagarajan et al., 2024). Thus, nutrient recovery is considered as one of an important technique for sustainable agricultural operations (Behjat et al., 2024).

Anaerobic digestion (AD) is a common bioprocessing method that treats nutrient-rich organic waste and produces biogas as a sustainable energy source and nutrient-rich digestate (Feng et al., 2023; Reilly et al., 2021). Food waste and poultry manure are some of the substrates that can be used to perform anaerobic digestion, which leads to the formation of a nutrient-enriched digestate (Nagarajan et al., 2023; Sarrion et al., 2023). The co-digestion of food waste and poultry manure has been recognized as one

of the strategies that can be adopted to ensure the stability of the process and enrich nutrients in the digestate (Ayantokun et al., 2025). Such enhancement can be attributed to the improvement of the carbon-nitrogen (C:N) ratio and quality of organic matter in the substrates (Li et al., 2025). Therefore, chicken droppings are high in nitrogen and phosphorus because of the incomplete digestion of nutrients from feed (Dróżdż et al., 2020), while food waste is an organic carbon source that helps in the digestion process thus providing an ideal environment for effective anaerobic digestion (Ayantokun et al., 2025). However, the direct application of solid digestate as fertilizer is constrained by numerous legal limits and issues regarding pathogenic contamination, which necessitates further processing for nutrient extraction (Vaneeckhaute et al., 2017). One of the methods that can be used for nutrient recovery from organic waste streams is struvite ($MgNH_4PO_4.6H_2O$) precipitation (Jupp et al., 2021).

Struvite is a slow-release fertilizer with satisfactory agronomic performance comparable to mineral fertilizers in diverse crop experiments (Liu et al., 2021; Mousavi et al., 2024). Struvite crystallization is controlled by pH, temperature, magnesium content and ionic strength of the solution, and it is dependent on the thermodynamic equilibrium constant (Rabinovich et al., 2021). The reaction for the formation of struvite is:

$$Mg^{2+} + NH_4^+ + \\ + PO_4^{3-} + 6H_2O \rightarrow MgNH_4PO_4.6H_2O$$

This reaction is thermodynamically favorable at pH 8-10 and equimolar concentrations of the ions (Kim et al., 2017).

Most studies on struvite crystallization have been carried out on the liquid fraction of the anaerobic digestate separated from solid fraction of digestate (Lorick et al., 2020; Mousavi et al., 2024; Nagarajan, Goyette, et al., 2024). However, the solid fraction of the digestate as a feedstock for struvite recovery has been less studied, despite its abundance in total nitrogen, phosphorus, and organic matter (Egene et al., 2021; Mazzini et al., 2020). The solid fraction of the digestate consists of both inorganic and organic-bonded phosphorus, which has to be dissolved in acid to crystallize. It requires further adjustment for various co-digestion substrates and retention times (Corona et al., 2021). Furthermore, many studies have investigated the effect of pH, magnesium-to-phosphorus (Mg:P) molar ratio, and mixing intensity on the effectiveness of struvite crystallization in liquid digestate (Moyo et al., 2023, 2024). However, the effect of hydraulic retention time (HRT) and mixing ratios of substrates on struvite recovery from the solid fraction of anaerobic digestate has not been sufficiently studied.

Various HRTs cause organic matter mineralization, thus changing the concentration and speciation of nitrogen and phosphorus in the solid fraction of digestate (Mazzini et al., 2020). The alteration of the substrate ratio affects the carbon-nitrogen-phosphorus (C: N: P) ratio of the co-digestate, the digestion process, and the subsequent recovery of nutrients (Yu et al., 2023). Such information gaps hinder the capability to build integrated waste management systems that couple anaerobic co-digestion with recovery of struvite from the solid fraction.

The aim of this study was to investigate the feasibility of struvite recovery from the solid phase of co-digested chicken droppings and food waste under varying digestion retention periods and substrate ratios. The specific objectives of this study were to (i) characterize the physicochemical properties of solid digestate fractions generated from anaerobic co-digestion of chicken droppings and food waste at different retention times of 15, 30 and 60 days for six substrate treatment ratios, (ii) assess the efficiencies of nitrogen (N) and phosphorus (P) recovery via struvite precipitation from the solid digestate fraction at the three retention times and (iii) determine the mass of struvite produced from the different chicken droppings and food waste ratios. This approach differs from the predominant practice in the literature, which employs the liquid fraction of digestate for struvite precipitation.

MATERIALS AND METHODS

Digestate source

Solid fraction of anaerobic digestate was generated in laboratory-scale anaerobic reactors at the Chemistry and Biochemistry Department, School of Science and Aerospace Studies, Moi University, Kenya. Six substrate treatments (Table 1) were incubated at 37 ± 1°C for 15, 30, or 60 days. Each treatment-hydraulic retention time (HRT) combination was established in three independent 300 mL reactors (six treatments × three HRTs × three replicates). The 15-, 30-, and 60-day observations

therefore originated from independent reactors. Each reactor received substrate and cow-dung inoculum at a 90:10 ratio. At the end of the assigned HRT, digestate from each reactor was centrifuged separately at 2,500 rpm for 15 min (Model: VMR Mega Star 600 benchtop centrifuge, Germany). The resulting solid fractions were retained separately for characterization, acid extraction, and precipitation experiments.

Digestate characterization

The solid fraction of the anaerobic digestate was subjected to comprehensive physicochemical characterization prior to struvite precipitation experiments. Parameters measured included pH, total solids (TS), volatile solids (VS), total Kjeldahl nitrogen (TKN), total ammonia nitrogen (TAN), orthophosphate (PO_4^3-P), and chemical oxygen demand (COD). pH measurements were conducted using a microprocessor pH meter (model: LT-10, Labtronics, India). Total solids and volatile solids were determined using the American Public Health Association (APHA) method (Eaton et al., 2005). Both TAN and TKN analyses were performed according to Kjeldahl methods (Behera, 2006), while phosphorus and COD were determined using colorimetric and closed reflux methods (Eaton et al., 2005), respectively. Additionally, the morphology of the recovered struvite was examined using a scanning electron microscope (SEM) (Model: JCM-7000, Benchtop SEM, JEOL, Japan) at the food fortification laboratory, Jomo Kenyatta University of Agriculture and Technology (JKUAT).

The physicochemical characteristics of the solid digestate across all treatments and retention times are summarized in Table 2. These data informed the selection of supplementary reagent doses for struvite crystallization experiments and provided the baseline concentrations for calculating nutrient recovery efficiencies.

Experimental setup

Phosphorus was extracted from the solid fraction digestate using a five-step protocol comprising dilution, acid dissolution, mixing, filtration, and drying, following the procedure recommended by Kutlar et al. (2024). Each solid fraction was diluted with distilled water to 10% TS. A 20% (v/v) hydrochloric acid (HCl) solution was added until pH 2.0 was reached, and the suspension was mixed at 250 rpm for 2 hours, consistent with the acidification approach described by Nagarajan et al. (2024). The mixture was then filtered, and the liquid phase is referred to throughout this manuscript as the acid extract.

After dissolution, 50 mL of acid extract was combined with 50 mL of 1 M $MgCl_2$ and 41.5 mL of 1 M KH_2PO_4, giving an initial reaction volume of 141.5 mL before pH adjustment. These additions provided magnesium and phosphorus in a molar ratio of 3:2.5 (Mg:P), suppling the ions required for struvite crystallization. As proposed by Nagarajan et al. (2024), 1 M NaOH and 1 M HCl solutions were used to regulate and maintain the pH at 9.0 in all treatments. The mixture was agitated at 240 rpm using a magnetic stirrer to facilitate uniform mixing and crystal nucleation. Stirring was continued for a further 3 minutes after pH stabilization to ensure complete ionic mixing.

After stirring, samples were allowed to settle overnight to permit complete precipitation. The precipitate was recovered by filtration through 0.45 µm Whatman filter paper. The recovered solid was oven-dried at 105°C for 24 hours to remove residual moisture and weighed to determine struvite mass yield per 50 mL of digestate extract. The efficiencies of phosphorus precipitation (Eq. 1) and nitrogen recovery (Eq. 2) were calculated as the percentage reduction in NH_4-N and PO_4-P concentrations in solution between the

Table 1. Description of treatments and substrate ratios used in the anaerobic co-digestion experiment

Treatments	Substrate ratios	Inoculum-substrate ratio
Food waste	100% FW	90% FW: 10% Inoculum
Chicken droppings	100% CD	90% CD: 10% Inoculum
T1	90% FW: 10% CD	90% T Sub: 10% Inoculum
T2	80% FW: 20% CD	90% T Sub: 10% Inoculum
T3	70% FW: 30% CD	90% T Sub: 10% Inoculum
T4	60% FW: 40% CD	90% T Sub: 10% Inoculum

Note: FW = food waste; CD = chicken droppings; T Sub = total substrate.

Table 2. Physicochemical properties of the solid digestate resulting from anaerobic co-digestion of chicken droppings and food waste across treatments and hydraulic retention times

HRT	Treatment	pH	TS (%)	VS (%)	TKN (mg/L)	TAN (mg/L)	COD (mg/L)
15	CD	7.11±0.04	15.84±0.08	80.63±0.71	4947±80.8	980±198	4720±226.27
15	FW	7.04±0.06	11.33±0.06	95.43±0.75	4293±80.8	910±99	7640±169.71
15	T1	7.03±0.01	16.97±3.43	63.96±14.66	5693±214	1960±198	6840±56.57
15	T2	7.24±0.03	19.78±4.06	65.96±14.54	5647±80.8	2590±99	5920±113.14
15	T3	7.56±0.04	23.03±0.45	66.69±2.80	7700±140	2520±198	5060±197.99
15	T4	7.11±0.02	20.80±0.01	65.96±8.55	6627±214	1400±198	4380±254.56
30	CD	7.51±0.04	19.29±0.10	65.25±1.51	6533±291	1260±0	4500±84.85
30	FW	7.10±0.06	11.63±0.62	93.09±2.26	3827±214	1050±99	6740±197.99
30	T1	6.97±0.02	18.94±0.14	80.80±0.15	4853±80.8	1050±99	6700±28.28
30	T2	7.50±0.01	20.04±0.87	78.19±0.73	6767±214	1120±198	5600±339.41
30	T3	7.48±0.02	23.10±0.02	60.21±0.18	7513±80.8	1190±99	4520±169.71
30	T4	7.71±0.02	23.95±0.21	59.79±0.75	8167±291	2590±99	3840±113.14
60	CD	7.12±0.03	19.21±0.98	57.10±12.13	9380±280	1260±198	3020±28.28
60	FW	7.01±0.03	10.40±0.05	94.22±0.04	4013±214	980±0	3580±141.42
60	T1	7.32±0.56	16.21±0.16	77.95±0.52	6300±140	1050±99	5640±169.71
60	T2	7.31±0.05	20.51±0.88	65.75±3.33	4807±80.8	1050±98	4840±395.98
60	T3	7.36±0.08	23.94±0.14	63.05±0.78	5833±214	1190±198	3280±452.55
60	T4	7.64±0.03	17.73±4.26	61.19±10.70	5553±214	1750±297	3260±197.99

Note: HRT = hydraulic retention time; TS = total solids; VS = volatile solids; TKN = total Kjeldahl nitrogen; TAN = total ammonium nitrogen; COD = chemical oxygen demand. Values are expressed as mean ± standard deviation (n = 3). CD = chicken droppings; FW = food waste; T1–T4 = treatment ratios as defined in Table 1.

pre-precipitation (Table 2) and post-precipitation (Supplementary Table S1) supernatants.

$$\text{Phosphorus precipitation efficiency (\%)} = = \frac{(P\ acid\ extract + P\ suplimented) - P\ liquid\ filtrate}{P\ acid\ extract + P\ suplimented} \times 100 \quad (1)$$

$$\text{Nitrogen recovery efficiency (\%)} = = \frac{N\ of\ precipitate}{N\ of\ digestate} \times 100 \quad (2)$$

Statistical analysis

Data were analyzed in R using a completely randomized factorial structure. For the six digestate treatments, two-way ANOVA was used separately for total phosphate precipitation efficiency, ammonium-N removal efficiency, and recovered precipitate mass, with substrate treatment, HRT, and their interaction specified as fixed effects. Model residuals were evaluated using Q-Q plots and the Shapiro-Wilk test, and homogeneity of variance was assessed using Levene's test. Statistical significance was set at $p < 0.05$. Where comparison with the synthetic control was required for precipitate mass, one-way ANOVA was conducted within each HRT followed by Dunnett's multiple-comparison test. Only statements supported by these analyses are described as statistically significant; otherwise, differences are described as observed differences in means.

RESULTS AND DISCUSSION

This section provides a detailed analysis of the feasibility of struvite formation under carefully designed operational conditions, in particular, the struvite production efficiency of six different solid fraction digestates of chicken droppings and food waste compositions using three different retention times as detailed in this study.

Phosphorus precipitation efficiency

Total phosphorus precipitation efficiency, calculated from PO_4-P depletion in the supplemented precipitation solution, ranged from 27.1% for FW at 15 days to 72.8% for T3 at 60 days (Figure 1). The mean efficiency increased from 15 to 60 days within each treatment and was generally higher in co-digestion treatments than in mono-substrate treatments. The maximum was observed for T3 (70% FW:30% CD) after 60 days.

Total phosphate precipitation efficiency increased from 15 to 60 days within all treatments (Figure 1). This pattern coincided with decreasing VS, particularly in CD (80.63% to 57.10%), whereas the change in FW was small (95.43% to 94.22%) (Table 2). Longer digestion may have altered phosphorus forms and the organic matrix, as reported previously (Mazzini et al., 2020; Xin et al., 2024; Yao et al., 2024), but phosphorus speciation and extraction efficiency were not measured here. The results therefore establish an HRT-related change in precipitation efficiency, not the mechanism responsible for it.

Substrate composition also affected the observed means. T2 and T3 generally exceeded the mono-substrate treatments, and T3 at 60 days produced the maximum efficiency (72.8%). However, indigenous PO_4-P concentrations in the acid extracts (17.4-41.5 mg/L) were negligible compared with the 1,285 mg P supplied as KH_2PO_4 per batch. Differences among treatments therefore more likely reflect the combined influence of ammonium availability and digestate-matrix effects than the measured indigenous phosphate concentration alone. At 15 days, for example, CD produced 47.4% precipitation compared with 27.1% for FW while their VS and TAN values also differed substantially.

The observed efficiencies obtained in this study are comparable to those reported for liquid digestate systems (Guida et al., 2021; Lorick et al., 2020; Mousavi et al., 2024), although direct comparison is limited by the external phosphate addition used here. Within the tested conditions, T3 (70%FW:30%CD) at 60 days was the best-performing treatment for combined phosphate precipitation.

Nitrogen recovery efficiency

Nitrogen recovery efficiency, calculated from the decrease in NH_4-N concentration between the pre- and post-precipitation solutions, ranged from 60.0% for FW at 60 days to 94.4% for T3 at 60 days (Figure 2). Co-digestion treatments generally maintained higher recovery efficiencies than the mono-substrate digestates, demonstrating the positive influence of substrate blending on nutrient recovery.

The effect of HRT on ammonium-N removal was treatment-dependent (Figure 2). Removal decreased from approximately 87% to 77% in CD and from 81% to 60% in FW between 15 and 60 days, whereas the co-digestion treatments remained comparatively high. Thus, unlike phosphate precipitation, ammonium-N removal did not increase consistently with HRT.

The higher recovery efficiencies in T1, T2, and T3 coincided with comparatively high TAN in several treatment-HRT combinations; at 15 days, T1-T3 contained 1,960-2,590 mg TAN/L (Table 2). Ammonium availability may therefore have contributed to precipitation when supplemented magnesium and phosphate were present (Guan et al., 2023; Mousavi et al., 2024). Although chicken droppings are naturally rich in nitrogen, the mono-substrate CD digestate still produced lower nitrogen recovery than the mixed treatments. This might be attributed to the presence of competing calcium (Ca^{2+}) and potassium (K^{+}) ions in chicken dropping digestate which affect the efficiency of struvite crystallization (Lorick et al., 2020). Competing ion, especially calcium (Ca^{2+}) can be formed precipitation of calcium phosphate in alkaline conditions (Moyo et al., 2024). Hence, the availability of phosphate ($PO4^{3-}$) ions in the solution may decreases and limits their involvement

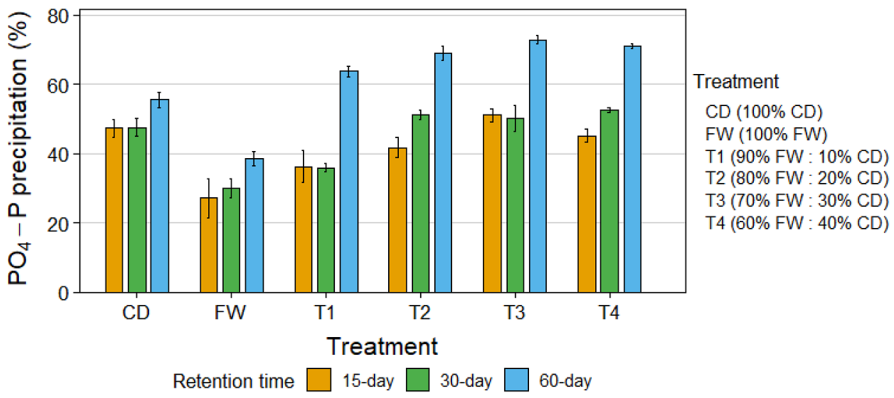

Figure 1. PO_4-P precipitation efficiency in supplemented acid-extract solutions across treatments and HRTs

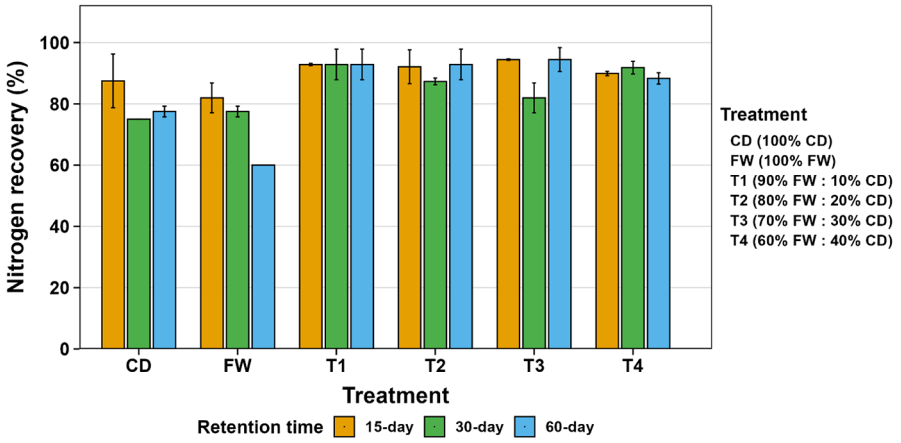

Figure 2. Percentage of nitrogen recovery from different treatment digestates in different retention times

in struvite crystallization (Moyo et al., 2024). Consequently, part of the available phosphate becomes unavailable for struvite formation, indirectly limiting ammonium incorporation into the crystal structure.

Overall. the recovery efficiencies were within ranges reported for liquid digestates (Kutlar et al., 2024; Mousavi et al., 2024; Nagarajan et al., 2024). The findings demonstrated that substrate composition exerted a greater influence on nitrogen recovery than hydraulic retention time alone. The T3 (70% FW:30% CD) treatment consistently provided the most favorable balance between ammonium availability and crystallization conditions, making it the optimum substrate composition for efficient nitrogen recovery through struvite precipitation.

Mass of recovered struvite precipitate

Recovered precipitate mass ranged from 8.31 to 10.80 g per batch (Figure. 3). Each batch contained 50 mL of digestate acid extract, 50 mL of 1 M $MgCl_2$, and 41.5 mL of 1 M KH_2PO_4, corresponding to an initial reaction volume of 141.5 mL before pH adjustment. Reporting the result relative to 50 mL of acid extract describes the amount of extract treated, but it does not mean that the precipitate originated from 50 mL of digestate alone. Because the batches received substantial Mg and phosphate supplementation, comparison with studies using different reagent inputs or volumes is not appropriate without normalization by molar input and product purity.

Among all treatments, the CD mono-substrate produced the highest precipitate mass (10.80 ± 0.03 g/50 mL) at 15 days of hydraulic retention time. This can be explained by the higher mineral content of the chicken droppings, especially calcium, magnesium, and phosphorus (Guida et al., 2021; Mousavi et al., 2024). However, the overall precipitate mass does not indicate better struvite formation. Calcium phosphates ($Ca_3(PO_4)_2$) and other co-precipitated mineral forms may constitute some of the overall precipitate mass and not pure struvite (Aguilar-Pozo et al., 2023). This is further confirmed by the fact that although the overall precipitate mass was higher (10.8 g) in the CD treatments, the phosphorus precipitation was still very low (47.3-55.5%) showing the existence of non-struvite phases in the precipitate. Similarly, Moyo et al. (2023) reported that high struvite production does not guarantee purity in digestate systems with high calcium content.

The co-digestate treatments (T1-T4) showed intermediate recovered precipitate yields ranging from 8.31 to 10.2 g/50 mL across all retention times. For instance, T4 (60% FW:40% CD) produced 9.8 g/50 mL at 30 days, while T3 (70% FW:30% CD) achieved 10.1 g/50 mL at 60 days, representing the highest yield among the mixed treatments corresponding with its PO_4-P concentration in co-digestion treatments. These treatments were characterized by relatively high concentrations of orthophosphate (38.5 mg/L, T3 at 60 days) and total ammonium nitrogen (2590 mg/L, T4 at 30 days), which promoted supersaturation and enhanced crystal growth during struvite precipitation (Nageshwari et al., 2022). Jang et al. (2023) similarly reported that the struvite precipitate yields are positively correlated to initial phosphate and ammonium concentration in the digestate. which is in line with the trend of

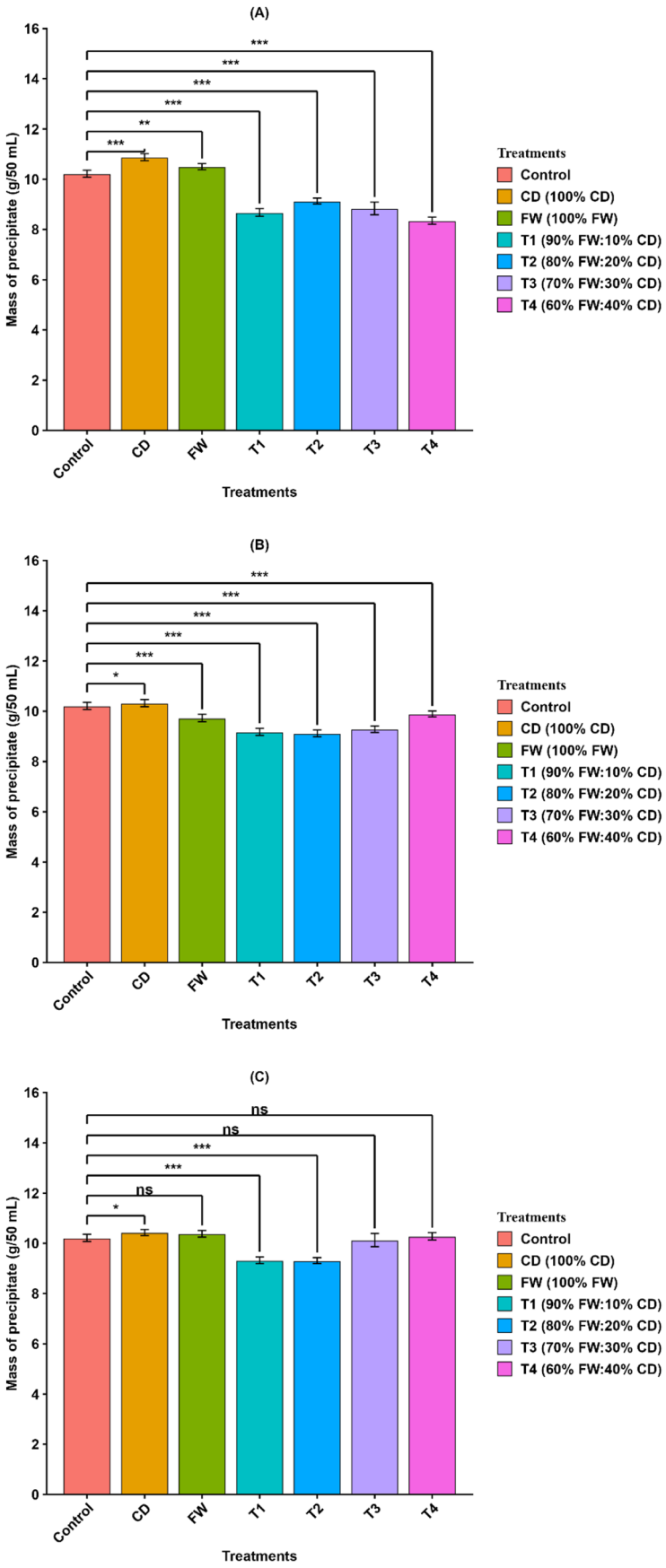

Figure 3. (A, B, and C). Recovered precipitate mass per batch at 15, 30, and 60 days. Each batch contained 50 mL acid extract, 50 mL of 1 M $MgCl_2$, and 41.5 mL of 1 M KH_2PO_4 (141.5 mL before pH adjustment) Asterisks show Dunnett comparisons with the synthetic control (ns, $p > 0.05$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$).

T4 with increasing hydraulic retention times. The highest values obtained from T3 at 60 days may corresponds with its higher phosphorus recovery efficiency, suggesting that prolonged digestion enhanced nutrient availability for crystal formation.

The FW mono-substrate produced struvite masses of 10.50, 9.70, and 10.30 g/50 mL acid extract at hydraulic retention times of 15, 30, and 60 days, respectively. The presence of high volatile solids in digestate (94.2% at 60 days, Table 2) might contribute to organic phosphorus molecules that will participate during acid dissolution, thereby further releasing phosphates to be used in struvite formation (Mousavi et al., 2024).

The synthetic control, prepared using ammonium sulfate [$(NH_4)_2SO_4$] as the nitrogen source, provided 10.21 g of struvite precipitation. The treatments with digestate in turn exhibited different outcomes from 8.31 g to 10.84 g/50 mL acid extract. However, the chicken droppings had a higher output than the control after 15 days. The higher yields obtained in the CD (100% chicken droppings) (10.84 g) and FW (100% food waste) (10.48 g) treatments compared to the control (10.21 g) may be due to the complex nature of the chemical composition of the anaerobic digestate. Unlike the synthetic control, digestates contain dissolved organic matter and competing ions, including calcium (Ca^{2+}), sodium (Na^{+}) and potassium (K^{+}). Calcium naturally co-precipitates as calcium phosphates in the manure-based system, which can increase the overall struvite mass output (Moyo et al., 2023). Moreover, the digestate extract may contain organic particles suspended in the solution that can provide nucleation sites, resulting in the physical entrapment of organic fragments in the crystal lattice, which was not seen for the synthetic control (Capdevielle et al., 2016; Guan et al., 2023).

The mass outputs in synthetic control (10.2 g) and 60-day co-digestion treatments (T3 = 10.1 g; T4 = 10.2 g) were the same, suggesting that prolonged anaerobic digestion improved nutrient mineralization to levels approaching those obtained with pure chemical reagent. Guan et al. (2023) similarly demonstrated that longer hydraulic retention time promotes the mineralization of organically bound phosphorus and nitrogen into soluble ionic forms suitable for struvite precipitation. Therefore, the solid fraction digestates are a feasible alternative for waste management. The efficacy of this method is comparable to the synthetic control (Li et al., 2025; Nagarajan et al., 2024). The findings of this study shown that acid extraction of the solid digestate followed by controlled struvite precipitation is an effective technique for recovering nitrogen and phosphorus while sporting sustainable digestate management within a circular bioeconomy.

Morphological analysis of the recovered precipitate

The scanning electron microscopy (SEM) micrographs showed substantial morphological variation among recovered precipitates. SEM images of all treatments (CD, FW, T1, T2, T3, and T4) and synthetic (as a control) digestate with their retention times (15, 30, and 60 days) captured at 1600× magnification and 10 µm scale are presented in the supplementary document (Supplementary Figure S1). Digestate-derived samples contained elongated prismatic or rod-like particles together with irregular aggregates and amorphous material. Some particles resembled morphologies previously reported for orthorhombic struvite crystal (Li et al., 2020), whereas the synthetic control displayed more uniform particle geometry and clearer edges (Supplementary Figure S1). These observations are described as struvite-like morphology; SEM alone does not establish phase identity, elemental composition, or purity.

SEM showed treatment- and HRT-related morphological differences (Supplementary Figure S1). Several 15- and 30-day samples contained fine particles within aggregates, while some 60-day samples displayed larger prismatic particles; T3 at 60 days showed relatively elongated particles with clearer faces. The irregular shapes, rough surfaces, aggregation, and amorphous coatings observed in digestate-derived samples are consistent with reported effects of organic matter, suspended particles, and competing ions (Ca^{2+}, K^{+}, Na^{+}) on crystal growth (Capdevielle et al., 2016; Nagarajan et al., 2024; Ochoa et al., 2021).

CONCLUSIONS

This study showed that acid extracts of solid digestate from chicken droppings, food waste, and their mixtures can be used as matrices for ammonium and phosphate precipitation after $MgCl_2$ and KH_2PO_4 supplementation. Total phosphate precipitation efficiency ranged from 27.1% to 72.8%, and ammonium-N removal ranged from 60.0% to 94.4%. Phosphate precipitation

generally increased with HRT, whereas ammonium-N removal did not: it decreased from 15 to 60 days in the CD and FW mono-substrate treatments and remained high in several co-digestion treatments. T3 (70% FW:30% CD) at 60 days gave the highest combined efficiencies. Recovered precipitate mass ranged from 8.31 to 10.80 g per 141.5 mL initial reaction batch containing 50 mL acid extract. SEM showed prismatic and rod-like particles consistent with struvite-like morphology together with irregular and amorphous material (Nagarajan et al., 2024).

From the above findings, it can be concluded that integrating anaerobic co-digestion with struvite crystallization provides an effective strategy for recovering nitrogen from the solid fraction of digestate while supporting sustainable digestate management and circular nutrient recycling. The results identify T3 (70% food waste:30% chicken droppings) digested at a hydraulic retention time of 60 days as the most suitable condition for maximizing nutrient recovery from the solid digestate fraction. Future research should examine the agronomic efficacy of recovered precipitate in field trials, evaluate the economic viability of scaling the acid dissolution precipitation process, and investigate strategies to minimize calcium co-precipitation to improve struvite purity in chicken manure-rich digestate systems.

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