



Nitrogen and phosphorus recovery from cow digestate by struvite precipitation: Process optimization to maximize phosphorus recovery

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ABSTRACT

The combination of the anaerobic digestion of waste biomass (e.g., livestock manure, energy crops and organic wastes) and the digestate treatment allows green energy to be obtained (starting from biogas/biomethane) and nutrients to be returned to the soil, satisfying the principles of the circular economy. Digestate has valuable potential as an organic fertilizer and soil amendment, as it can be an important source of nutrients, nitrogen and phosphorus (N and P), essential for crop growth. However, digestate production sometimes exceeds the capacity of nearby lands to use the nutrients. Therefore, the recovery of nutrients from digestate has become an important task for anaerobic digestion plants, to meet current regulations. In this study, a method combining struvite precipitation and ammonia stripping was tested in the laboratory to better understand the nutrient removal/recovery efficiency of the two nutrients. Results indicate that more than 60% of total P was removed as struvite, which can be used in N–P fertilizer, substituting synthetic mineral fertilizers.

The recovery of N and P from digestate by struvite crystallization allows the removal of nutrient excess at farm level, reducing the environmental impacts of using slurry/digestate in agriculture. The recovery of struvite allows the production of a fertilizer that can be easily exported from farms, promoting the circular economy.

1. Introduction

The twentieth century witnessed a clear change of course from the use of organic fertilizers to synthetic fertilizers. In particular, nitrogen (N) based fertilizers have been and still are produced by the Haber-Bosch process, using an energy-consuming and extremely impactful reaction that converts molecular nitrogen (N₂) into ammonia (NH₃) [1]. Phosphorus (P) is extracted from mineral reserves which are non-renewable and are now becoming severely depleted [2,3]. The massive and unchecked use of these two nutrients has led to serious environmental problems, mainly linked to eutrophication phenomena. These compromise the water quality of surface water bodies [4–7] and lead to a dramatic reduction in biodiversity [8–10]. In addition, there are also worries about the supply of nutrients in future and about food safety [11].

In this context, nutrient recovery processes can play an important role in limiting the use of synthetic fertilizers, while ameliorating all the problems linked to their use (e.g., environmental impact, biodiversity reduction, P reserves depletion). Nutrient recovery from digestate represents an opportunity to recover N and P. In fact, various studies

suggest that nutrients in the digestate could satisfy the global demand for fertilizers [12–14].

Digestate is a by-product of the anaerobic digestion process and is obtained from the microbial decomposition of raw materials used for biogas production. The partially decomposed organic matter, coming out from digestors, has a total solid (TS) content and biodegradability index (BI) distinctly lower than that of the biomass fed into the digestors [15,16]. Composition of the outcoming biomass depends on the composition of the raw materials and the conditions of the operating process [17].

Moreover, a high concentration of nutrients is still contained in digestate. Microbial metabolic activity is not able fully to decompose the organic components into mineral nutrients during the anaerobic digestion process itself [18]. Instead, nutrients are made more available because they are partially converted from their organic forms into inorganic forms by microbial processes [19]. So digestates have halfway features between an organic amendment and a mineral fertilizer.

Even though digestate has potentially positive aspects in terms of nutrient recycling, in particular for P, it can also have negative repercussions on the environment if mismanaged. Thus, the agronomic use

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of digestate is regulated by directives from the European Union [20] in which two contexts are identified: i) areas vulnerable to nitrates, with a limit of 170 kg of N ha⁻¹ per year, and ii) areas not vulnerable to nitrates, in which the ceiling is 340 kg of N ha⁻¹ per year.

Clearly the simple agronomic use of digestate may not represent a feasible solution, since the useable agricultural area (UAA) may well be above the locally available farm area. Hence, field applications repeated over time may lead to serious overloading of nutrients because of the limited arable land available to companies. It is therefore necessary to identify innovative solutions that allow the removal/recovery of the N dissolved in the digestate, as well as the P [20–28].

This is becoming especially important nowadays, since biogas/biomethane plants are on the rise, in line with the ecological transition to an effective way to reduce greenhouse gases [29]. In Italy there are now 2000 biogas plants, compared to just 150 in 2017 [30]. This trend involves a significant increase in the mass of digestate produced, which must inevitably be subjected to treatment processes. Nutrient recovery from digestate can take an important role in terms of reducing the necessity for the purchase of mineral fertilizers based on N and P and contribute to restricting the impacts on their respective biogeochemical cycles [10,31,32] in compliance with the circular economy (Fig. 1). Literature has proposed many different approaches for removing N and P, but to the best of our knowledge, removing P from digestate still needs to be better tested.

The aim of this work is to identify a new combined process for nutrient recovery from digestate which uses two simultaneous processes: i) struvite precipitation and ii) ammonia stripping. Previously, N and P removal from digestate has already been tested by our group with good results when working on pig slurry-derived digestate [33]. Unfortunately, at that time a first attempt at working with cow digestate gave poor results, suggesting that a new approach would be needed in performing the experiments. Moreover, the previous work [33] did not consider the variation of other parameters than the Mg/P ratio, such as pH and the agitation system.

To be precise, therefore, the present research represents a novelty because it evaluates the effects of a combination of struvite precipitation

and ammonia stripping to recover both nutrients, P and N, from cow digestate. Moreover, various different conditions were tested in this study to identify the best operating process to maximize nutrient recovery. In particular, the effects of pH values, Mg:P molar ratio and type of agitation (mechanical or with air flow) were examined.

2. Materials and methods

2.1. Theoretical basis

Struvite precipitation allow simultaneous recovery of ammonium and orthophosphate, with the addition of an appropriate magnesium (Mg) external source. Therefore, N and P, respectively in the forms of ammonium (NH₄⁺) and phosphate (HPO₄²⁻), can precipitate as struvite or Magnesium Ammonia Phosphate (MAP) according to the following relationship (Equation (1)):



The presence of Mg²⁺, NH₄⁺ and HPO₄²⁻ ionic species is indispensable for struvite precipitation. This reaction involves the formation of a hard crystalline deposit when the molar ratio of Mg:N:P is greater than 1:1:1 [34]. Since cattle manure already contains a fair amount of P and N, it is enough to add defined quantities from an external source of Mg to allow struvite precipitation. One of the fundamental parameters for chemical precipitation is the pH, which has been suggested to be optimal in the range of 7–11 [35].

The supersaturation condition is the factor driving struvite precipitation and influences the induction time of crystallization [36,37]. It is described by a supersaturation index (SI) indicated in the study of Stolzenburg et al. [38] as follows (Equation (2)):

$$\text{SI} = \log \left(\frac{\alpha_{\text{Mg}^{2+}} \bullet \alpha_{\text{NH}_4^+} \bullet \alpha_{\text{HPO}_4^{2-}}}{K_{\text{struvite}}} \right) \quad (2)$$

where K struvite is the solubility product of struvite, while αi is the species' ion activity.

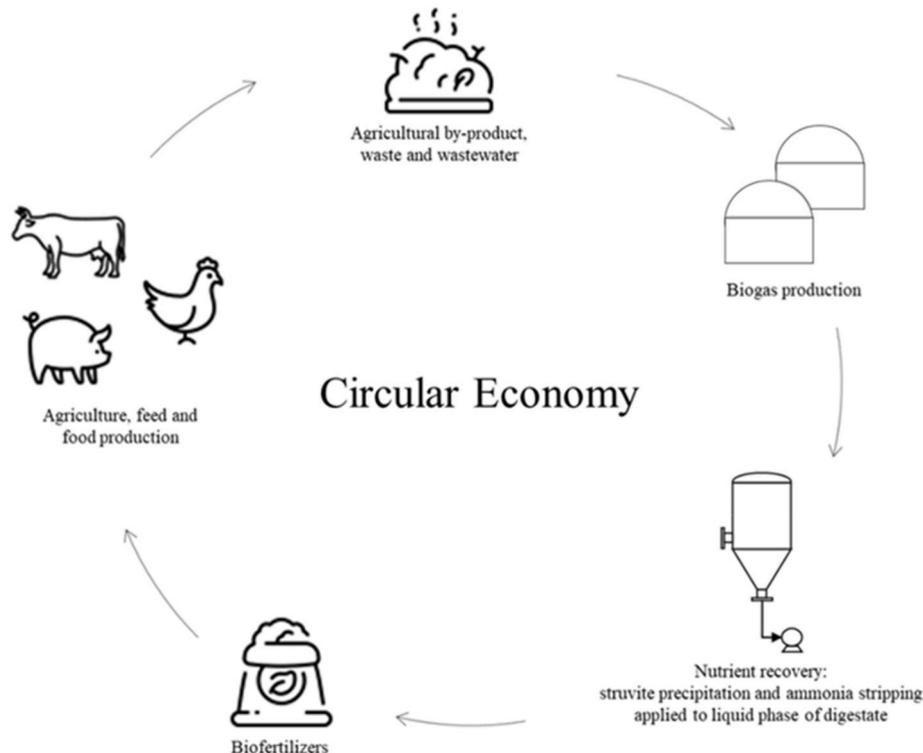


Fig. 1. Diagram of the circularity introduced by the combination of anaerobic digestion and nutrient recovery from the digestate.

The trend of struvite formation as a function of the supersaturation index is explained by the Fang et al. study [39].

In our study, the supersaturation condition was determined by Visual MINTEQ 3.1 software, through which it was possible to predict the formation and precipitation of struvite [40]. The software is able to prevent struvite precipitation in particular conditions defined by the operator, who enters the pH value, and concentration of ionic species (Mg^{2+} , NH_4^+ and PO_4^{3-}). Then, a forecast model is developed by software which predicts the compounds' behavior (remain in solution or precipitate).

Struvite is a ternary salt that provides a slow-release rate of nutrients compared to traditional chemical fertilizers and represents an effective alternative source to rock phosphate to maintain agricultural productivity [41]. Moreover, the characteristics of struvite prevent nutrient loss through leaching and surface runoff [42–44].

Ammonia stripping is a physicochemical process for N removal/recovery from digestate through two thermodynamic equilibria (Equations (3) and (4)):



The way to remove N from digestate by volatilization is intervene on two different parameters: i) temperature, and ii) pH, which allow the shifting of both reactions to the left or to the right side (Equations (3) and (4)). Hence, for the N to be released as a gas it is necessary to raise the temperature and/or pH of digestate.

The N removed is recovered through an acid trap of sulfuric acid (H_2SO_4), which reacts with NH_3 to form ammonium sulphate $(NH_4)_2SO_4$ (Equation (5)), a salt recognized as an N fertilizer for agricultural use [45], mainly indicated for alkaline or neutral soils [46].



2.2. Experimental materials

The raw digestate originated from a large-scale biogas plant at a cattle-breeding farm, located in Villanova sull'Arda, Piacenza (Italy). The biogas plant was operated continuously at mesophilic conditions (40 °C) with cattle manure at an organic loading rate (OLR) of 1.75 kg volatile solids (VS) $m^{-3} d^{-1}$ and a hydraulic retention time (HRT) of 30 days.

For this experiment raw digestate was used, i.e. the outgoing product of the anaerobic digester without any physical treatment for solid-liquid separation. The characteristics of the digestate are indicated in Table 1 (as average of three samples).

2.3. Experimental analysis

Total solids (TS), total ammonia nitrogen (TAN), total phosphorus (TP), inorganic P, pH value, and electrical conductivity (EC) were

Table 1

Characteristics of raw digestate from anaerobic digester treating cattle manure and by-products of agriculture.

Parameters	Value
pH	8 ± 0
TS ^a (% FM ^b)	6 ± 1
TAN ^c (mg L ⁻¹)	2261 ± 106
TP ^d (mg L ⁻¹)	174 ± 17
PO ₄ ^{3-e} (mg L ⁻¹)	86 ± 20

^a TS: total solids.

^b FM: fresh matter (on a wet weight basis).

^c TAN: total ammonia nitrogen.

^d TP: total phosphorus.

^e PO₄³⁻: phosphate.

assessed using the standard methods [47].

TS content was determined by thermobalance (RADWAG MA 110.R) set at 105 °C to constant weight [48]. TAN, inorganic P and TP were determined by spectroscopic analysis according to the Nessler method, using the molybdenum blue method before and after mineralization with diluted (65%) nitric acid HNO_3 , respectively [47]. The pH value was measured with appropriate laboratory equipment (Hanna Instrument, HI5221-02). All analyses were performed in triplicate and data reported represent the means of three replicates.

2.4. P recovery by struvite production and N removal: flask scale

Firstly, struvite precipitation and ammonia scrubbing flask tests were compared under different operating conditions. In particular, the effects induced by different i) pH, i.e. 8.5 or 9.5, ii) Mg:P molar ratio, i.e. 1.3 or 2, and iii) type of stirring, i.e. mechanical or by air flow, were studied. Digestate moisture content, i.e., TS content, can affect also process performance but, in this case, TS digestate (TS = 6 ± 1%) well represented TS average content of cow digestates, i.e. 6.4 ± 1.24 (n = 6) [49]. Further studies will need to vary digestate parameters such as moisture, total N, TAN and TP contents.

The pH was adjusted with 1 mol L⁻¹ of sodium hydroxide (NaOH) to reach the required pH values (8.5 or 9.5). The Mg:P molar ratio of 1.3 or 2 was obtained by adding a 20% (w/v) magnesium chloride $MgCl_2$ solution. Finally, the agitation of the digestate was performed with magnetic stirring (500 rpm) or with airflow (1 LPM). Furthermore, to avoid problems of digestate leakage, a few drops of antifoam were added.

Eight different tests were carried out with a hydraulic retention time (HRT) of 16 h (Table 2). During this period, samples were collected (at 60, 120, 180, 240, and 960 min from the start) in order to build a record of the trend of P and N reduction in the digestate and the chemical and physical differences.

Therefore, each sample was analyzed to define pH, TS, TAN, TP and PO₄³⁻ according to the previous paragraph (all analyses were performed in triplicate).

2.5. P recovery by struvite precipitation production and N removal: crystallizer lab-scale

Based on the results obtained from the flask tests, a small-scale laboratory prototype crystallizer was designed and built to seek the best combination of the different factors. In particular, two different tests were carried out under the following conditions: i) high pH value (pH of 10) which, in addition to favoring struvite precipitation, allowed us to strip off a greater N amount; ii) the same Mg:P molar ratios, i.e. 1.3 and 2; iii) air flow of 9.0 LPM as a method of stirring (Table 3).

Another important variation from the previous tests was the basifying agent. Unlike in the previous tests, the pH value of 10 was modulated with a 1 mol L⁻¹ calcium hydroxide $Ca(OH)_2$ solution. The reason lies in the properties of the two cations Ca^{2+} and Na^+ ; in fact, the first one, as a bivalent cation, is a good flocculant, while the second one, as a monovalent cation, has dispersing and destructive properties for the physical structure of soil. Therefore, looking towards a future

Table 2

Experimental design of the tests conducted in flasks by varying the 3 parameters: pH, Mg:P.

Sample	Volume (mL)	pH	[Mg:P]	Agitation
FS1	900	8.5	1.3	magnetic stirring (500 rpm)
FS2	900	8.5	2.0	magnetic stirring (500 rpm)
FS3	900	9.5	1.3	magnetic stirring (500 rpm)
FS4	900	9.5	2.0	magnetic stirring (500 rpm)
FS5	900	8.5	1.3	air flow (1 LPM)
FS6	900	8.5	2.0	air flow (1 LPM)
FS7	900	9.5	1.3	air flow (1 LPM)
FS8	900	9.5	2.0	air flow (1 LPM)

Table 3
Experimental design of the tests conducted by varying the Mg:P molar ratio.

Sample	Volume (mL)	pH	[Mg:P]	Agitation
CLS1	2000	10	1.3	Air flow (9 LPM)
CLS2	2000	10	2	Air flow (9 LPM)

industrialization of the process, it was essential to carry out the tests with $\text{Ca}(\text{OH})_2$ rather than an NaOH solution. Antifoam was also added.

A compact polycarbonate (PC) crystallizer was specifically designed to reproduce the optimal conditions for struvite precipitation (Fig. 2). Specifically, this lab-scale prototype allowed a supersaturated condition to be reached, which ensured struvite nucleation and growth, enhanced by the airflow which entered through a plate diffuser placed at the bottom of the crystallizer. The volume of the crystallizer was 2 L and HRT was fixed at 16 h.

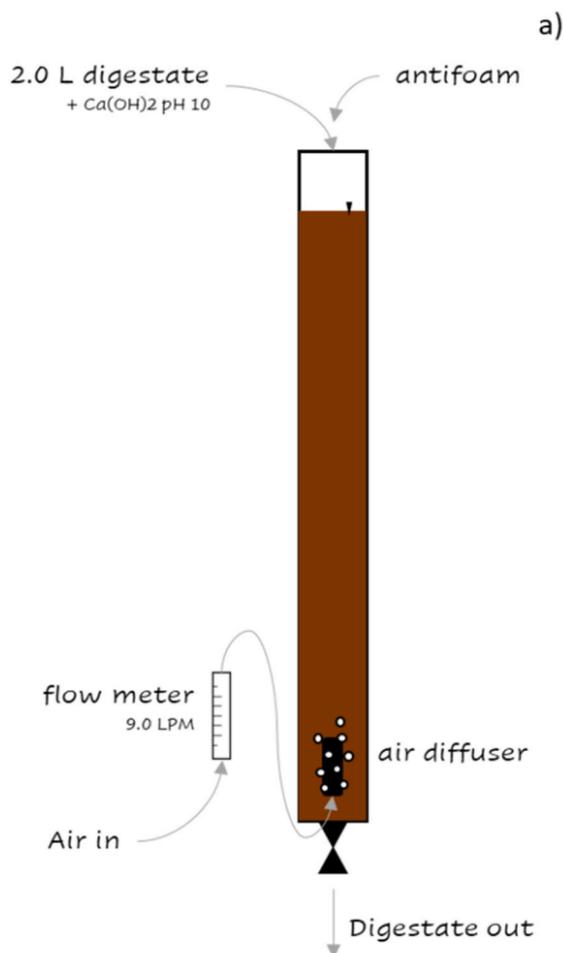
As before, samples were collected at 60, 120, 180, 240, and 960 min from the start, in order to build a record of the trend of P and N reduction in the digestate and the chemical and physical differences in terms of pH, EC, and TS.

3. Results and discussion

3.1. Struvite precipitation

The amount of P recovered in the form of struvite precipitate was calculated according to following mass balance (Equation (6)):

$$[\text{PO}_4^{3-}]_{\text{total}} = [\text{PO}_4^{3-}]_{\text{struvite}} + [\text{PO}_4^{3-}]_{\text{residual}} \quad (6)$$



Because $[\text{PO}_4^{3-}]_{\text{struvite}}$ was calculated starting from values of $[\text{PO}_4^{3-}]_{\text{total}}$ and $[\text{PO}_4^{3-}]_{\text{residual}}$ measured by a spectroscopic method, the P difference represents the amount of struvite precipitate in form of phosphate (e.g., magnesium phosphate, calcium phosphate) [50,51].

3.2. Ammonia stripping

The amount of N removed from digestate was determined according to following mass balance (Equation (7)):

$$[\text{NH}_4^+]_{\text{total}} = [\text{NH}_4^+]_{\text{struvite}} + [\text{NH}_4^+]_{\text{stripping}} + [\text{NH}_4^+]_{\text{residual}} \quad (7)$$

In this case, the known values are $[\text{NH}_4^+]_{\text{total}}$, $[\text{NH}_4^+]_{\text{residual}}$ and $[\text{NH}_4^+]_{\text{struvite}}$; the first two measured by the spectroscopic method and the last obtainable by a simple stoichiometric calculation, respectively. To be specific, the latter one represented about 1% of total ammonia. So, the $[\text{NH}_4^+]_{\text{stripping}}$ was obtained from the difference of all values.

3.3. Effect of the conditions for struvite precipitation and ammonia stripping process: flask scale

Result showed an average P recovery efficiency of $51.8 \pm 7.8\%$. By analyzing each case studied, interesting evidence emerged, as explained below (Table 4).

The pH comparison demonstrated an increase in P removal at the higher value. In fact, at the lower pH value of 8.5, the removal average was of $44.11 \pm 9.56\%$, while $52.16 \pm 6.66\%$ was obtained at a pH of 9.5, for samples moved with magnetic stirring ($p < 0.05$). Similar effects were found for the samples treated by air flow, for which the average P

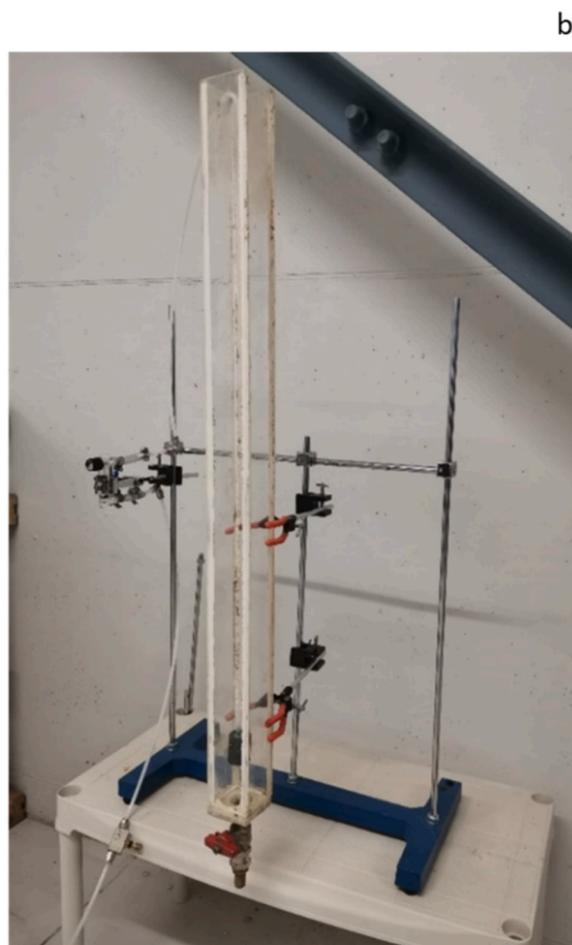


Fig. 2. Diagram of the lab-scale reactor used for the nutrient removal and recovery test and photo.

Table 4

Results of Phosphorus and Nitrogen recovery/removal (%) in the flask experimental test, each characterized by specific operating conditions.

Sample	Operating conditions			TP removed (%)	PO ₄ ³⁻ recovery (%)	NH ₃ stripped (%)	N recovery (struvite) (%)
	pH	[Mg:P]	Agitation				
FS1	8.5	1.3	magnetic stirring (500 rpm)	50 ± 6	74 ± 6	40.9 ± 6.6	0.6 ± 0.1
FS2	8.5	2.0	magnetic stirring (500 rpm)	38.2 ± 10.2	73 ± 17	42.3 ± 2.3	0.59 ± 0.14
FS3	9.5	1.3	magnetic stirring (500 rpm)	49.4 ± 8.1	79 ± 13	43.9 ± 0.4	0.6 ± 0.1
FS4	9.5	2.0	magnetic stirring (500 rpm)	54.9 ± 6.1	83.5 ± 10.6	39.6 ± 5.5	0.68 ± 0.09
FS5	8.5	1.3	air flow (1 LPM)	52 ± 1	77.5 ± 2.1	31.5 ± 14.2	0.63 ± 0.02
FS6	8.5	2.0	air flow (1 LPM)	51.7 ± 4.1	77 ± 7	29.1 ± 11.8	0.62 ± 0.06
FS7	9.5	1.3	air flow (1 LPM)	56 ± 2	86.5 ± 3.5	32 ± 10	0.70 ± 0.03
FS8	9.5	2.0	air flow (1 LPM)	61.4 ± 2.4	94 ± 6	65.6 ± 6.7	0.76 ± 0.05

removal values were of $51.87 \pm 2.46\%$ against $59.05 \pm 3.36\%$ ($p < 0.05$) for samples with pH set to 8.5 and 9.5, respectively. Moreover, the pH effect was more evident in the tests carried out with airflow, while it was less marked for those with magnetic stirring. These results agree with those of various previous studies in which greater P removal efficiency was reported at high pH values [52–54].

The Mg:P molar ratio showed marked differences, in particular, at high pH value. At a pH of 9.5, in conditions of magnetic stirring, the P removed was of $49.43 \pm 8.13\%$ and of $54.89 \pm 6.10\%$ with 1.3 and 2.0 Mg:P molar ratios, respectively; while at pH of 8.5 the situation was completely the opposite: the lower Mg:P molar ratios showed an increase of P removal, whereas the higher molar ratios did not. P removal values were of $50 \pm 5.69\%$ and of $38.22 \pm 10.16\%$ with 1.3 and 2.0 Mg:P molar ratios, respectively. In the samples treated by air stirring, higher P removal values were measured at 2 Mg:P molar ratio at 9.5 pH, while the values measured at pH 8.5 were lower.

The stirring technology used turned out to be fundamental in terms of P removal. Higher average percentage values of P removal ($p < 0.05$) were measured for samples treated by air flow compared to those in which magnetic stirring was used, i.e. P removal of $55.46 \pm 4.71\%$ and $48.13 \pm 8.76\%$, respectively.

Moreover, from the measurements carried out, no influences of the HRT were found. After 1 h of the process, the PO₄³⁻ was completely precipitated.

The amount of N precipitate as struvite was calculated stoichiometrically, starting from Equation (1), based on the quantity of struvite produced by the reaction. The percentage of N recovery in struvite was equal to $0.65 \pm 0.08\%$, in agreement with that reported by the Shim

et al. study [55]. The highest value of N recovery as struvite calculated was obtained in tests FS7 and FS8, respectively of $0.70 \pm 0.03\%$ and $0.76 \pm 0.05\%$; while the other tests showed values between 0.59 and 0.68 (Table 4).

The remaining part of the N was released, most likely, in the form of NH₃, as seen from Equation (3) of N stripping. As expected, for high pH values, the reactions reported in Equations (3) and (4) were shifted to the left; in other words, towards the production of NH₃. Furthermore, the most successful condition, which guaranteed the removal of N from the digestate, was that found in test number 8, with 9.5 pH values and 1 LPM of airflow. Unlike what was found for PO₄³⁻ removal, the N removal from digestate was HRT-dependent, as shown in Fig. 3.

Hence, the best combination of factors in the flask tests was in tests FS7 and FS8, characterized by values of pH 9.5 and treatment by airflow.

3.4. Effect of the conditions for struvite precipitation and ammonia stripping process: lab-scale crystallizer

The results obtained from the two laboratory tests carried out showed an overall reduction of P equal to $37.64 \pm 10.16\%$ and $57.47 \pm 1.62\%$ for tests CLS1 and CLS2, respectively (Table 5). Similar values were observed to those in the flask tests, in which P removal of $56.61 \pm 2.03\%$ and of $61.49 \pm 2.44\%$ were measured, respectively for tests FS7 and FS8. Hence, a certain consistency of values obtained on a small scale was demonstrated.

The P recovery rate did not appear to be affected by HRT, as was found previously. The P reduction was already reached after 1 h and it remained constant for the following 16 h.

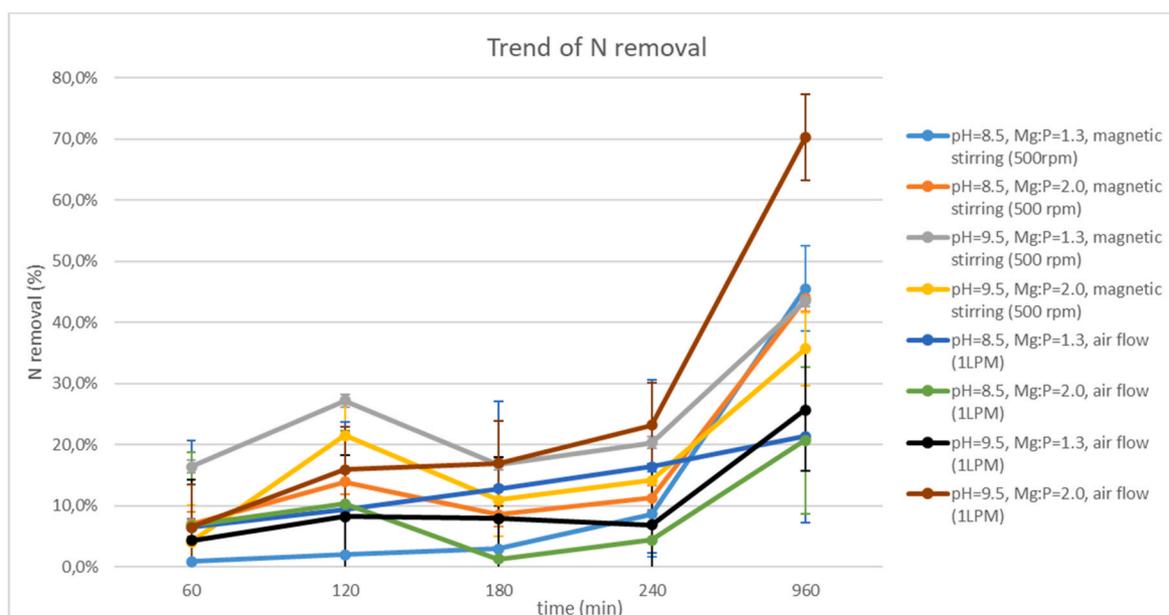
**Fig. 3.** Trend of total N (%) removal from digestate by struvite precipitation and ammonia stripping processes.

Table 5

Experimental results from two tests carried out with a lab-scale crystallizer.

Sample	Operating conditions			TP removed (%)	PO ₄ ³⁻ recovery (%)	NH ₃ stripped (%)	N recovery (struvite) (%)
	pH	[Mg:P]	Agitation				
CLS1	10	1.3	air flow (9 LPM)	37.64 ± 10.16	75 ± 15	57.90 ± 7.40	0.60 ± 0.10
CLS2	10	2.0	air flow (9 LPM)	57.47 ± 1.62	79.50 ± 2.10	61.60 ± 9.20	0.63 ± 0.02

However, N results were strongly influenced by the HRT and the inlet airflow. In fact, the nutrient removal percentage varied from an initial 7.79% to a final 59.16% for the CLS1 test; for the second test (CLS2) an initial value of 6.12% was recorded, with 68.15% reached after 16 h. Moreover, on increasing HRT from 16 h to 24 h, the N removal percentage was greater and equal to 86.9% (data not reported in this work).

From a test carried out previously (not reported) under the same conditions but with an airflow set at 1.0 LPM, it was possible to underline the significant difference induced by the greater inlet airflow: high flow rates led to greater movement of the mass and a higher volatilization of N.

3.5. Physical parameters

The different samples of digestate, collected at different times, were assessed for moisture content and, therefore, for TS.

From the values collected, a tendency towards a decrease in the TS content (% wet weight) in the liquid fraction of digestate was observed, most likely due to the precipitation of struvite (Table 6).

4. Conclusion

In this research, a combined process for digestate treatment was tested to identify the physical conditions which will guarantee the good removal and subsequent recovery of the P and N. In particular, struvite precipitation and ammonia stripping with an acid trap process could be selected as the best available technologies for fertilizers production: MgNH₄PO₄ · 6H₂O and (NH₄)₂SO₄.

From the various experimental tests performed, it emerged that the most efficient combination provides: i) high pH values (≥9.5) that favor the struvite precipitation and, contextually, guarantees greater N stripping; ii) rapid airflow (9 LPM), which allows a more rapid struvite precipitation and higher degree of N stripping; and iii) Mg:P molar ratio of 1.3 for good struvite formation, since a further contribution of Mg is not justified by the results obtained.

This digestate technology treatment will next be implemented at an industrial scale to evaluate its efficiency and related operating costs, particularly for energy and chemical use, and to improve the quality and predictability of the fertilizers produced.

The struvite precipitation process could play an important role to recover the P, and therefore to counteract the substantial reduction in nutrient reserves, besides providing a solution to problems arising from an increase in the number of biogas plants.

In this context, a low-cost crystallizer plant could be put into the biogas chain after the screw-press and before the decanter. The decanter would make it possible to recover the whole fraction of P precipitated as struvite in the solid fraction of the digestate and thus represent an excellent amendment enriched in P.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marcello Salvatori reports financial support was provided by Puglia Region. Fabrizio Adani reports financial support was provided by Sistemi Energetici Spa. Fabrizio Adani reports a relationship with Sistemi Energetici Spa that includes: consulting or advisory. No one.

Table 6

Total solids percentage in liquid fractions.

Sample	Operating conditions			TS (%)
	pH	[Mg:P]	Agitation	
FS0	–	–	–	2.62 ± 0.40
FS1	8.5	1.3	magnetic stirring (500 rpm)	2.44 ± 0.13
FS2	8.5	2.0	magnetic stirring (500 rpm)	2.18 ± 0.12
FS3	9.5	1.3	magnetic stirring (500 rpm)	2.11 ± 0.02
FS4	9.5	2.0	magnetic stirring (500 rpm)	2.02 ± 0.24
FS5	8.5	1.3	air flow (1 LPM)	2.29 ± 0.25
FS6	8.5	2.0	air flow (1 LPM)	2.28 ± 0.31
FS7	9.5	1.3	air flow (1 LPM)	2.01 ± 0.01
FS8	9.5	2.0	air flow (1 LPM)	1.89 ± 0.04

Data availability

No data was used for the research described in the article.

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