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Nutrient recovery from digested waste: Towards a generic roadmap for setting up an optimal treatment train



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ABSTRACT

This paper aims to develop a generic roadmap for setting up strategies for nutrient recovery from digested waste (digestate). First, a guideline-based decision-tree is presented for setting up an optimal bio-based fertilization strategy as function of local agronomic and regulatory criteria. Next, guidelines and evaluation criteria are provided to determine the feasibility of bio-based fertilizer production as function of the input digestate characteristics. Finally, a conceptual decision making algorithm is developed aiming at the configuration and optimization of nutrient recovery treatment trains. Important input digestate characteristics to measure, and essential factors for monitoring and control are identified. As such, this paper provides a useful decision-support guide for wastewater and residuals processing utilities aiming to implement nutrient recovery strategies. This, in turn, may stimulate and hasten the global transition from wastewater treatment plants to water resource recovery facilities. On top of that, the proposed roadmap may help adjusting the choice of nutrient recovery strategies to local fertilizer markets, thereby speeding up the transition from a fossil-reserve based to a bio-based circular nutrient economy. © 2018 Elsevier Ltd. All rights reserved.

1. Introduction

A recent review of nutrient recovery technologies for treatment of digested waste, i.e. digestate, has highlighted the potential for nitrogen (N) recovery as ammonium sulfate (AmS) fertilizer, as well as for phosphorus (P) recovery as struvite, MgNH₄PO₄:6H₂O, and/or calcium (Ca)/magnesium (Mg)-P precipitates (Vaneeckhaute et al., 2017a). Through field trials and greenhouse experiments (Rahman et al., 2014; Thompson, 2013: Vaneeckhaute et al., 2014, 2016), the agronomic potential of these fertilizers has been demonstrated. The economic and ecological benefits of bio-based fertilization scenarios using these products have also been confirmed (Vaneeckhaute et al., 2013). Nevertheless, implementation of nutrient recovery strategies is still limited due to regulatory constraints, operational problems associated with the variability of the quality and quantity of the fertilizers produced, as well as the persisting uncertainty of fertilizer sales and the inconsistency of marketing prices in regions where commercialization is possible (Carey et al., 2016; Guest, 2015; Rahman et al., 2014; Seymour, 2009; USEPA, 2013; Vaneeckhaute et al., 2017a). Finding the appropriate combination and sequence of technologies to treat a particular waste stream and the optimal operating conditions for the overall treatment train are key concerns (Carey et al., 2016; Vaneeckhaute et al., 2017a).

To facilitate configuration and optimization of integrated nutrient and energy recovery treatment trains, a novel generic nutrient recovery model (NRM) library has recently been developed (Vaneeckhaute et al., 2018) as a complement to the standard biological-oriented model libraries provided by the International Water Association (Rieger et al., 2012). It involves integrated biological-physicochemical mathematical process models for anaerobic digestion, P precipitation/crystallization, and N stripping and absorption. The NRM library was subjected to a global sensitivity analysis (GSA) so as to find the main factors that impact a wide range of 25 performance indicators of an energy and nutrient recovery treatment train, including methane and biogas production, digestate composition and pH, ammonium sulfate recovery, struvite production, purity, particle size and density, air and



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chemical requirements (acid, base), scaling potential, among others (Vaneeckhaute, 2015). The GSA provided important (new) generic insights in the interactions between process inputs and outputs for the three different digested waste streams studied to date, i.e. digested sewage sludge, digested manure, and a codigestion mixture (Vaneeckhaute, 2015).

For all processes included in the NRM library and the GSA analyses (see above: anaerobic digestion, P precipitation/crystallization, N stripping/absorption), the variation related to the input digestate physicochemical composition resulted in a major effect on the nutrient and energy recovery potential through its direct effect on the operational pH and ionic strength. Major (new) findings involve: (1) the impact of chloride (Cl) inhibition on ammonia removal in the stripping unit, suggesting that MgO or Mg(OH)₂ is to be preferred over MgCl₂:6H₂O for preceding P precipitation as struvite, (2) the impact of calcium (Ca), iron (Fe), and aluminum (Al) inhibition on P recovery in the precipitation unit, suggesting the inclusion of a Ca/Fe/Al precipitate separator after the anaerobic digester, and (3) the interaction between Fe/Al, sulfur (S), and methane (CH_4) production in the anaerobic digester. By using MgO/Mg(OH)₂ in the struvite precipitation unit, pH is increased which is also beneficial for subsequent ammonia stripping and thus reduces the need for base addition (Vaneeckhaute, 2015). Finally, if struvite is to be recovered, implementation of the precipitation unit after digestion is also beneficial, since the GSA results showed that higher temperatures increase struvite purity (less co-precipitation).

These essential insights in the interactions between nutrient and energy recovery unit processes acquired from GSA were successfully used to set up an optimal treatment train configuration for resource recovery from bio-waste (Vaneeckhaute, 2015). However, it was revealed that the optimal configuration and associated operational conditions (pH, temperature, etc.) also depend on local fertilizer markets, which in turn depend on local fertilizer regulations and agronomic aspects (e.g., soil P saturation status), next to the high influence of the digestate characteristics. Such data are highly variable in time and space, which makes the selection of nutrient recovery processes and their operational settings highly complex. Hence, the development of a user-friendly decisionsupport tool for optimal configuration of energy and nutrient recovery facilities based on case-specific waste characterization, as well as regulatory and agronomic criteria, seems highly valuable, although lacking in literature and in practice to date.

In order to assist industries and municipalities in the decision making process, this paper aims to provide a generic decisionsupport roadmap for setting up optimal nutrient recovery strategies as function of local fertilizer markets and digestate physicochemical characteristics. The scope of the study includes anaerobic digestion and the selected best available technologies (and resulting bio-based products) applied at full scale for the recovery of nutrients as marketable fertilizer commodities (Vaneeckhaute et al., 2017a), i.e. P precipitation/crystallization (struvite, Ca/Mg-P precipitates), NH₃ stripping/absorption (AmS fertilizer), and acidic air scrubbing (AmS fertilizer). The selection of these technologies (and products) was made based on the stage of implementation, the technical performance, and financial aspects, next to the fertilizer marketing potential. Besides the information acquired through field-scale experimentation and modelling (Vaneeckhaute, 2015), additional data were obtained through extensive contact with technology providers. Hence, the roadmap is partially based on full-scale operational experience. Important factors for input waste characterization, monitoring and control were identified. As such, the roadmap provided in this paper may function as a helpful decision-support tool for residuals and wastewater processing utilities considering the implementation of anaerobic digestion and subsequent recovery and recycling of nutrients as marketable agricultural commodities.

2. Methods

Two important factors determining the optimal treatment train configuration for nutrient recovery are i) local fertilizer markets, and ii) physicochemical characteristics of the digestate to be treated. The overall methodology for developing a generic roadmap for setting up nutrient recovery strategies as function of these factors is presented in Fig. 1.

The method involves the identification of roadmap objectives related to the factors defined above, the identification of data needs to assess these objectives, data collection, data integration in guideline-based decision-trees or algorithms, and the actual selection of roadmap outcomes, i.e. products to be recovered, technologies to be implemented, and configurations of integrated nutrient and energy recovery treatment trains.

In view of end-product marketing, a first important roadmap objective is to identify local fertilizer markets and hence local product demands. The latter depends on both agronomic data, such as the soil P saturation status and the bio-fertilizer characteristics, and regulatory data, such as maximum nutrient application standards and fertilizer quality specifications. Such data were obtained through experimental field and greenhouse trial research (e.g., Sigurnjak et al., 2017; Vaneeckhaute et al., 2014, 2016), as well as from literature and through contact with governmental authorities, agronomic agencies, and technology providers in the field (Table 1). Based on the collected information, a guidelinebased decision-tree of bio-based fertilization recommendations as function of local agronomic criteria (soil P saturation status) and regulatory criteria (maximum allowable application rate for N and P), was produced. The latter can be used to determine which bio-based products have the greatest marketing potential in the region under study.

Next, an important roadmap objective is to **determine the initial feasibility** of nutrient recovery based on the input nutrient contents of the digestate under study. Data needs involve minimum P and N contents in digestates at which the technologies under study can become economically and technically feasible, a well as optimal N:P ratios for struvite production. Such data were inventoried through contact with the most established technology providers in the field as identified in Vaneeckhaute et al. (2017a) (Table 1). Based on the identified feasibility criteria, the initial feasibility of producing the fertilizers selected in objective 1 can be evaluated, and an initial technology selection can be made.

Finally, an important roadmap objective is to optimize the integration of the selected unit processes in a treatment train for nutrient recovery, taking into account both input digestate physicochemical characteristics and fertilizer market demands. To this end, operational data (e.g., pH and temperature), as well as insights in interactions between energy and nutrient recovery unit processes must be obtained. Such data and insights were collected for anaerobic digestion, struvite precipitation/crystalliza tion, and NH₃ stripping/absorption through modelling and global sensitivity analyses using the new nutrient recovery model library (see Introduction; Vaneeckhaute et al., 2018), as well as extensive contact with technology providers (Table 1). The data were integrated in a conceptual algorithm for nutrient recovery from digestate with decision making criteria related to physicochemical parameters of the waste stream under study and local fertilizer market demands (see objective 1 above). As such, the developed algorithm can be used to select an optimal nutrient recovery treatment train configuration based on digestate characteristics and fertilizer markets for the case under study. The latter depends on both agronomic data, such as the soil P saturation status and the biofertilizer characteristics, and regulatory data, such as maximum nutrient application standards. Such data were obtained through



Fig. 1. Methodology for roadmap development: Identification of objectives and associated data needs, data collection, data integration, and outcome selection.

experimental field and greenhouse trial research (e.g., Sigurnjak et al., 2017; Vaneeckhaute et al., 2014, 2016), as well as from literature and through contact with governmental authorities, agronomic agencies, and other stakeholders in the field.

3. Results and discussion

In relation to the three objectives described above, the developed generic roadmap for setting up nutrient recovery strategies as function of fertilizer markets and digestate physicochemical characteristics involves three steps to be executed by the enduser, which are presented and discussed below.

Step 1: Set up a bio-based fertilization strategy as function of local agronomic and regulatory criteria

If one wants to install a treatment train for nutrient recovery, first contact should be sought with local/ regional agronomic agencies and/or consultants in order to obtain insights in fertilizer related regulation and the corresponding market demand. If no local market would exist for recovered nutrient products, interest can be sought abroad. Depending on the targeted region. N or P can be the limiting factor for manure and digestate application as organic/organo-mineral base fertilizer. The latter determines for which fertilizers the market demand is the highest in the particular region. Fig. 2 provides a guideline-based decision-tree of bio-based fertilization recommendations as function of local fertilizer regulation and agronomic criteria. As is the case to date in many regions, a maximum allowable fertilization standard is assumed for N application from organic or organo-mineral fertilizer products (=base fertilizer) and for N application from mineral fertilizers (e.g., CRAAQ, 2010; MAP4, 2011). Another standard is set for total P. Note that K application was not included in the recommendations, since currently no regulatory standards exist for K.

If N is the limiting factor for fertilizer application, which is the case in P-poor regions, e.g., Brazil, Russia, Argentina, Western Africa, Northern Germany, etc. (MacDonald et al., 2011), digestate may be applied to the field in its crude form, or mixed with some liquid fraction if solid-liquid separation would take place, up to the maximum allowable N level for base fertilizer application. Additional bio-based N fertilization up to the level for mineral fertilizers can occur using AmS which contains a high immediate N use efficiency (Vaneeckhaute et al., 2014). However, struvite may also be applied for this purpose. The choice will depend on the crop's nutrient demand in time, the soil type, and the local product availability: the application of AmS is interesting as starter fertilizer or for additional fertilization of direct available N during spring or summer (Vaneeckhaute et al., 2014), whereas struvite may provide a source of slow-release N and P (Rahman et al., 2014). If the availability of both products would be restricted and/or transportation costs unacceptably high, it may be required to apply chemical N in order to reach the N fertilization recommendation standard. Nevertheless, since to date air scrubbers are required at most farms, anaerobic digestion plants, and manure/digestate processing facilities in order to avoid NH₃ emissions to air (Melse et al., 2009), future practice should focus on the maximum recovery of the resulting AmS. In addition, Ca/Mg-P precipitates could be applied up to the maximum allowable level for P fertilization. Also, Prich solid fractions, locally available or imported from P-rich regions (see dashed line from right to left in Fig. 2), could be used for this purpose. However, in that case, the N content of the solid fraction also has to be taken into account when setting up the fertilization strategy. In summary, in P-poor regions, among the considered best available bio-based products to date, the agricultural demand for digestate (base fertilizer), recovered AmS and/or struvite, and Ca/Mg-P fertilizers is expected to be high.

In P-saturated regions, e.g., Flanders, Québec, Eastern China, Italy, Northern Spain, etc. (MacDonald et al., 2011), standards for P application are or will become increasingly strict due to historical manure and/or chemical fertilizer surpluses on the soil balance and the resulting environmental pollution (Sutton et al., 2013). This means that the P supply via manure and/or mineral fertilizers. whether chemical or bio-based, is under pressure and that P is mainly supplied through mining of the soil complex (Sutton et al., 2013). Previous research has shown the interest of mechanically separating the digestate in order to obtain a P-poor liquid fraction, and as such to apply more available N as base fertilizer for the same amount of P (Sigurnjak et al., 2017; Vaneeckhaute et al., 2014). Moreover, it was observed that mixtures of digestate and its liquid fraction can increase the use efficiency of soil P (Sigurnjak et al., 2017; Vaneeckhaute et al., 2014). Hence, application of these products could stimulate crop uptake of P. Additional mineral fertilization up to the maximum allowable N level could then occur using AmS. Hence, overall, in P-saturated regions, among the considered recycled products, the most interesting fertilizers for agricultural purposes are likely the liquid fraction of digestate (as base fertilizer, whether or not mixed with raw digestate) and AmS.

Note that in this case, most of the P ends up in the organic solid fraction after solid-liquid separation, which is usually exported to P-poor regions because local markets are restricted (see dashed line from right to left in Fig. 2). However, in light of the depleting natural P resources and soil organic carbon contents (Sutton et al., 2013), interest is growing in maximum recovery of P from the liquid fraction of digestate as struvite, Ca/Mg-P fertilizer, or P-rich solution. As such, pre-treatments that stimulate P release in the liquid fraction during solid-liquid separation gain importance in P-saturated regions, e.g., acidification and mechanical pre-treatments (Gonzalez-Fernandez et al., 2008; Vaneeckhaute et al., 2017b). Meanwhile, local valorization of the valuable organic matter that

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Roadmap objective	Data needs	Data source
1. Identify local fertilizer markets	Agronomic data (bio- fertilizer characteristics, soil P saturation status)	 Previous experimental work: Vaneeckhaute et al. (2014, 2016) and Sigurnjak et al. (2017) Agronomic agencies: Inagro – Research and Advice Center in Agricul- ture and Horticulture (BE), Vlaco – Flemish compost organization (BE) Technology providers: Ostara (CA). Innova Energy (BE)
	Regulatory data (maximum nutrient application standards, fertilizer quality specifications)	 Governmental authorities: Flemish coordination center for manure pro- cessing (BE), European Commission, European Sustainable Phosphorus Platform (ESPP)
2. Determine the initial feasibility of nutrient recovery	Minimum P content, minimum N content, optimal N:P ratio	 Technology providers: Ostara (BC), Colsen (NL), Anaergia (CA), NuReSys (BE), Europe Environnement (FR), RVT Process Equipment (DE), GNS (DE), Branch Environmental Corp (USA) Previous literature review: Vaneeckhaute et al. (2017a)
3. Optimize the integration of unit processes in a treatment train for nutrient recovery	Process operational data (pH, temperature, and additional process-specific requirements discussed in roadmap Step 3 below)	 Technology providers: Ostara (BC), Colsen (NL), Anaergia (CA), NuReSys (BE), Europe Environnement (FR), RVT Process Equipment (DE), GNS (DE), Branch Environmental Corp (USA) Previous literature review: Vaneeckhaute et al. (2017a)
	Interactions between unit processes	 Previous modelling work and global sensitivity analyses: see Introduc- tion and Vaneeckhaute et al. (2018)



Fig. 2. Guideline-based decision-tree of bio-based fertilization recommendations as function of local fertilizer regulation and agronomic criteria. AmS = ammonium sulfate; LF = liquid fraction; Green box = agronomic decision criteria; Red-framed box = regulatory decision criteria; Orange box = fertilization recommendation; Dashed line = optional pathway.

ends up in the solid fraction can be stimulated, since the latter contains an improved, i.e. higher, C:P ratio (Vaneeckhaute et al., 2017b). The recovered mineral P fertilizers could also be recycled locally, e.g., for horticultural purposes or for cultivation of specific crops that require lots of P, such as potatoes, beets, and maize (Hillel, 2008; see dashed line on the right side in Fig. 2).

Step 2: Evaluate the initial feasibility of bio-based fertilizer production as function of the input digestate physicochemical characterization

An important point to consider when designing nutrient recovery systems is the physicochemical characterization of the digestate to be treated. Obviously, first the macronutrients, especially N and P, of the digestate have to be measured and quantified in order to check whether there is effectively an interest for N and P recovery. As such, technology providers claim that, in general, P recovery becomes of interest if the P load is higher than 80 kg d^{-1} , whereas N recovery using air stripping and scrubbing becomes economically feasible at concentrations in the range of 400–500 mg N L⁻¹. Moreover, struvite production is only of interest if the digestate has N:P molar ratio above 1 (Le Corre et al., 2007). The optimal N:P ratio to maximize struvite recovery and purity would be higher than 6 according to technology providers. Below that ratio, significant co-precipitation, e.g., with Ca-P, is to be expected (Huchzermeier and Wengdong, 2012; Le Corre et al., 2005). If, based on the above criteria, the recovery of N and P seems feasible, additional physicochemical analyses will have to be conducted in

order to set up an optimal nutrient recovery treatment train configuration (see Step 3).

Step 3: Use the conceptual algorithm for treatment train configuration and optimization

Fig. 3 provides the conceptual algorithm developed based on the findings in this research and extensive contact with technology providers.

It gives an overview of decision-support guidelines for configuration of nutrient recovery treatment trains, taking into account input digestate characteristics and fertilizer market demands. The various treatment train configurations per feasibility scenario (Step 2) are described below. Note that for confidentiality reasons, manufacturer names are not provided.

(a) N and P recovery not feasible

Clearly, if there is **no interest in N and P recovery** (Step 2: digestate nutrient contents are too low to make recovery feasible), then no action should be taken, unless regulatory discharge criteria are to be met. Minor contents of N and P can be removed and recovered using a low-cost final effluent treatment. Ion exchange and sorption processes are of increased interest for this purpose (Carey et al., 2016; Vaneeckhaute et al., 2017a). Additional treatment in lagoons prior to discharge may also provide a solution (Olguin et al., 2017). However, in that case, large areas of land can be required. Alternatively, the water could be reused, e.g., as irrigation water, if quality requirements are met, or the water can be recycled to a nearby wastewater treatment plant. The latter is usually located onsite in case of sewage sludge digestion.

(b) P recovery not feasible, N recovery feasible

If there is **only interest in N recovery** (Step 2: P load of the digestate is too low to make P recovery feasible), the recommended

digestate treatment train configuration concerns NH_3 stripping and acidic air scrubbing, with optional pre- and post-treatments, depending on the composition of the digestate (Fig. 3: Configuration 1).

Next to the N content, important input digestate physicochemical characteristics that may influence the configuration and capital/operating costs and that thus should be monitored are the total suspended solids (TSS) and chloride (Cl) contents, as well as the input alkalinity (Vaneeckhaute, 2015). In general, the lower the input TSS and Cl contents, the better the ammonia stripping performance. Excess TSS (>2%) must usually be removed using a solid-liquid phase separation unit prior to stripping (Bonmati and Flotats, 2003; Quan et al., 2010). However, some companies recently developed a stripper-scrubber system without packing that allows stripping of the raw digestate with high TSS content, up to 8-9%, e.g., the AMFER technology (Colsen, 2015) and AnaErgia's ammonia recovery system (Anaergia, 2014; Vaneeckhaute et al., 2017a). Excess Cl (>20 mol m⁻³; Vaneeckhaute, 2015) removal is more complicated. It could potentially be achieved through ion exchange or sorption (Pelin et al., 2013; Williams et al., 2015), though the feasibility of implementing such treatments remains to be evaluated, along with the impact of the present chlorides on the stripping performance (Vaneeckhaute, 2015). Input alkalinity should be checked to determine whether the addition of base (most often NaOH in order to minimize scaling) is required for pH increase in the stripper. Usually the digestate alkalinity (4000–6000 mg L^{-1} as CaCO₃) is sufficient to satisfy the pH requirements by stripping out CO₂, without the use of chemicals (Anaergia, 2014). In that case, it is interesting to select a stripping process without packing column in order to avoid CaCO₃ precipitation on the packing (Vaneeckhaute et al., 2017a). Overall, depending on the input characteristics of the digestate (mainly the TSS content and alkalinity) and market requirements (e.g., fertilizer pH), the most suitable stripping technology should be selected for each specific case. Indeed, to date, the operating conditions of the stripping and acidic air scrubbing processes and



Fig. 3. Conceptual algorithm for configuration and optimization of nutrient recovery treatment trains. Dashed lines indicate recycle flows. AmS = ammonium sulfate; TSS = total suspended solids; Red-framed box = decision criteria; Green box = recovery strategy; Grey box = technology selection; Orange box = operational action.

the composition of the recovered AmS-solution highly depend on the technology provider.

Next to the above optional pre-treatments, the main operational factors to control in the stripping process itself are the temperature and pH (USEPA, 2000). In the scrubbing column, the AmSsolution can be recycled until the preferred AmS concentration is reached, which should be in the range of 25-40% according to technology providers. Higher concentrations are not recommended because they may cause unwanted AmS precipitation on the stripping column, whereas lower concentrations provoke high transportation costs (Mehta et al., 2015; Vaneeckhaute et al., 2017a). Therefore, the system is usually operated in semi-continuous mode, where the AmS concentration is monitored (usually pH measurements are sufficient) and the solution is discharged when product specifications are met (Bonmati and Flotats, 2003). The effluent N and P concentration, as well as other qualitative parameters, should then be checked against discharge regulations or recommended quality levels for water reuse which depend on the application. Technology providers state that, in most cases, it is economically more attractive to recover only 80-90% of the N using the air stripping and scrubbing technology, and to add a more low-cost alternative for the final effluent treatment up to discharge/reuse levels. Reuse as irrigation water may provide an interesting solution. Alternatively, the water could be recycled to a nearby wastewater treatment plant.

(c) P recovery feasible, N recovery feasible or not feasible

If **P recovery is of interest** (Step 2: P load of the digestate is sufficiently high to make P recovery feasible), one should first check whether there exist a market for struvite at acceptable transportation costs (see Step 1) and whether the N:P molar ratio is suitable for struvite precipitation (see Step 2). Hence, two scenarios are possible: (i) struvite and AmS recovery (depending on the N content) are targeted (Fig. 3: Configuration 2), or (ii) the N:P ratio and/or fertilizer markets are not favorable for struvite recovery and Ca/Mg-P precipitation is targeted, whether or not in combination with AmS recovery (Fig. 3: Configurations 3–4). The latter depends on the N content of the digestate.

In the first case (Fig. 3: Configuration 2), it is recommended to implement struvite precipitation prior to stripping in order to avoid unwanted precipitation in the stripping unit. However, in this case, $Mg(OH)_2/MgO$ should be used as Mg source for struvite precipitation instead of MgCl₂ in order to avoid Cl inhibition in the subsequent stripper (see Introduction and Vaneeckhaute, 2015). Note that this configuration has the additional advantage that often no more base is required for pH increase in the stripper. Indeed, model simulations show that the pH increase through Mg addition and CO₂ stripping is usually sufficient to achieve high NH₃ removal efficiencies (Vaneeckhaute, 2015). Prior to implementation, one should check whether iron (Fe) or aluminum (Al) dosing occurred upstream, e.g., for sludge conditioning, since these components may influence the struvite recovery potential and product quality. In Vaneeckhaute et al. (2016) and Larsen et al. (1959), for example, it was revealed that FePO₄ sludge is not interesting as P fertilizer from an agronomic point of view because of Fe-P fixation. This is likely also the case for Al because of the comparable P binding properties of trivalent Fe and Al (Mengxue et al., 2016). Hence, for waste streams containing high Fe and/or Al contents, implementation of a phase separation unit for precipitate removal after digestion is recommended. Indeed, it was observed in Vaneeckhaute (2015) that Fe and Al precipitation could already start in the digester. Obviously, also the TSS content of the digestate (limit: 1000 mg L^{-1} according to technology providers) will determine whether or not a solid-liquid phase separation unit needs to be installed. Note that, if there is an interest in applying acidification as pre-treatment for improved P release during solid-liquid separation, attention should also be paid to the impact of salts (mainly chlorides, see above) on the stripping performance when selecting the chemical, e.g., HCl, to be used.

In addition, important factors to monitor are the molar N:P, Ca: P, and Mg:P ratios of the input waste stream. Calcium may seriously hinder struvite precipitation and product purity (Le Corre et al., 2005; Huchzermeier and Wengdong, 2012; Vaneeckhaute, 2015). In case of high Ca contents relative to N and Mg, the addition of Ca(OH)₂ in the phase separation unit is recommended to induce precipitation and removal of CaCO₃ (Huchzermeier and Wengdong, 2012). However, the pH should then be controlled at a value lower than 10 to avoid P losses through Ca-P precipitation (Le Corre et al., 2005; Vaneeckhaute, 2015), unless there would be a market for the resulting separated Ca-P-rich solid fractions (see Step 1). Next, the Mg:P ratio should be adjusted and the pH controlled according to Fig. 2 in order to obtain optimal struvite recovery (Le Corre et al., 2007). Usually, the process is operated such that it reaches the discharge levels for P. Subsequently, AmS recovery can take place if N levels are sufficiently high, as described above (Fig. 3: Configuration 1).

In the second case (Fig. 3: Configurations 3–4), i.e. the N:P ratio is **not favorable for struvite recovery** or local regulations do not stimulate struvite application, excess P can be recovered through Ca/Mg-P precipitation, whether or not in combination with AmS production (depending on the N content). In this case, the temperature used in the anaerobic digestion process may influence the digestate treatment train configuration. Indeed, overall Vaneeckhaute (2015) revealed that P recovery through Ca-P precipitation is maximal at low temperatures and high pH. Hence, if the digestate would be produced using thermophilic digestion (optimal temperature: 50-57 °C; Tchobanoglous et al., 2003), it is likely more feasible to implement AmS recovery prior to Ca-P precipitation in order to save on heat requirements (Fig. 3: Configuration 4). The heat can then be recovered from the digestate, thereby cooling down the digestate for subsequent precipitation of P. Moreover, if the stripper is operated to achieve N:P molar ratios below 1, then the absence of N in the recovered P fertilizer product can somehow be guaranteed (Le Corre et al., 2007).

On the other hand, if a mesophilic (optimal temperature: 30– 38 °C; Tchobanoglous et al., 2003) or psychrophilic (optimal temperature: 12–18 °C; Tchobanoglous et al., 2003) digestion takes place, then Ca-P production should preferably take place prior to stripping in order to avoid precipitation in the stripping unit and reduce/eliminate chemical requirements for stripping (Fig. 3: Configuration 3).

In any case, the most important operational factors for monitoring and control are the pH and temperature. This again underlines the fundamental importance of accurate pH and temperature calculations in nutrient recovery models as proposed by Vaneeckhaute et al. (2018).

If there is no market for struvite nor Ca/Mg-P precipitates, but precipitation is required to reach the discharge/reuse levels for P, then these mineral fertilizers can be mixed with the separated organic solid fraction and exported to P-poor regions after pasteurization. This is the common practice in high-nutrient regions.

It should also be noted that in each of the above cases, the installation of an acidic air scrubber is recommended and often obliged in order to capture NH₃ losses during digestate processing. The captured NH₃ can then again be recovered as AmS solution.

Finally, an important remark for the roadmap presented in this paper is that other potential recovered products apart from those selected in Vaneeckhaute et al. (2017a), such as concentrates from membrane filtration (De Hoop et al., 2011; Velthof, 2011), were not yet considered. Nevertheless, if the production of other bio-based fertilizers from digestate proves to be viable at a large scale, then

the roadmap will have to be extended by inclusion of these nutrient products. Model-based optimization of promising nutrient recovery processes may help speeding up their implementation. Another remark is that no particular attention was given to K and S fertilization in the above roadmap. Nevertheless, the crop demand for these nutrients may additionally influence the optimal fertilizer choice and nutrient recovery strategy. Hence, when more bio-based products become available, the roadmap should also be further diversified in terms of macronutrients other than N and P.

4. Conclusions

A generic three-step decision-support roadmap for setting up strategies for nutrient recovery from digestate was presented. It involves:

- A guideline-based decision-tree of bio-based fertilization recommendations as function of local agronomic and regulatory criteria;
- 2. Guidelines and evaluation criteria for determining the feasibility of nutrient recovery based on operational experience;
- 3. A conceptual algorithm for configuration and optimization of nutrient recovery treatment trains as function of input digestate characterization and fertilizer markets.

As such, this paper provides a user-friendly decision-support tool and useful guidance for wastewater and residuals processing utilities considering the implementation of nutrient recovery practices. If the production of new bio-based fertilizers at a large scale proves to be feasible, the roadmap should be further extended to allow for the integration of these products and technologies. In that case, it can also be important to further diversify the roadmap in terms of macronutrients, other than N and P. Finally, this study demonstrated the primary importance of monitoring, optimization and control of temperature and pH in the nutrient recovery systems under study.

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