Roadmap for setting up an optimal treatment train configuration for nutrient recovery from (digested) residuals

Vaneeckhaute C[1,4], Belia E[2], Meers E[3], Tack FMG[3], Vanrolleghem PA[4]
[1]BioEngine – Research team on green process engineering and biorefineries, Chemical Engineering Department, Université Laval, 1065 ave. de la Médecine, Québec, QC, Canada, G1V 0A6, celine.vaneeckhaute@gch.ulaval.ca
[2]Primodal Inc., 145 Rue Aberdeen, Québec, QC, Canada, G1R 2C9
[3]EcoChem, Laboratory of Applied Ecochemistry, Ghent University, Coupure Links 653, Ghent, Belgium
[4]model*EAU*, Université Laval, 1065 ave. de la Médecine, Québec, QC, Canada, G1V 0A6

ABSTRACT

This paper advances the development of a generic roadmap for setting up strategies for nutrient recovery from digested waste. First, guidelines were presented to set up an optimal bio-based fertilization strategy as function of local/region-specific fertilizer legislations. Next, instructions were provided to evaluate the feasibility of bio-based fertilizer production as a function of input waste characteristics. Finally, an algorithm was developed aiming at the configuration and optimization of nutrient recovery treatment trains. Important input waste characteristics to measure, and essential factors for monitoring and control were identified. As such, this paper should provide a useful and comprehensive 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.

KEYWORDS

anaerobic digestion, mathematical modelling, process design, renewable fertilizers, residuals management, resource recovery, waste valorization

INTRODUCTION

A recent review of nutrient recovery technologies for digestate treatment (Vaneeckhaute et al., 2017) has highlighted the potential for nitrogen (N) recovery as ammonium sulfate (AmS) fertilizer (Bonmati and Flotats, 2003), as well as for phosphorus (P) recovery as struvite, $MgNH_4PO_4{:}6H_2O$ (and/or calcium (Ca) / magnesium (Mg)-P precipitates) (Rahman et al., 2014). Through field trials (Vaneeckhaute et al., 2014) and greenhouse experiments (Vaneeckhaute et al., 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 inconsistency of marketing prices in regions where commercialization is possible (Seymour, 2009). Indeed, the fact that water resource recovery facilities

(WRRFs) must aim at delivering high-value products that can partially replace those produced by other means (e.g., chemical mineral nitrogen (N) production through the Haber-Bosch process) leads to a paradigm shift in specifications of the outputs of the facility: no longer treated wastewater and biosolids, but products that have to compete with what is already on the market. Finding the appropriate combination and sequence of technologies to treat a particular waste flow and the optimal operating conditions for the overall treatment train are key concerns (Carey et al., 2016; Guest, 2015).

This paper aims to provide a roadmap for **setting up optimal nutrient recovery treatment train configurations as function of waste stream (digestate) properties, as well as local/regional fertilizer legislations and markets.** 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., 2017), i.e. P precipitation/crystallization (struvite, Ca/Mg-P precipitates), NH_3 stripping/absorption (AmS fertilizer), and acidic air scrubbing (AmS fertilizer). The selection of these technologies (and products) was made on the basis of the stage of implementation, the technical performance, and financial aspects, next to the fertilizer marketing potential. Besides the information acquired in Vaneeckhaute (2015), additional data were obtained through contact with technology providers. Hence, the roadmap is (partially) based on full-scale operational experience. As such, this paper may provide a helpful tool for residuals and wastewater processing utilities considering the implementation of anaerobic digestion and subsequent recovery and recycling of nutrients as marketable agricultural commodities.

METHODS

First, a generic nutrient recovery model (NRM) library was developed and validated at steady state (Vaneeckhaute, 2015), including mathematical process models for the best nutrient recovery systems currently available (as identified in Vaneeckhaute et al., 2017). Dynamic physicochemical three-phase process models for precipitation/crystallization (target product: struvite), stripping and acidic air scrubbing (target product: ammonium sulfate) as key unit processes were developed. In addition, a compatible biological-physicochemical anaerobic digester model was built. The latter includes sulfurgenesis, biological nitrogen, phosphorus, potassium, and sulfur transformations, interactions with organics, among other relevant processes, such as precipitation, ion pairing, and liquid-gas transfer. The models are based on detailed solution speciation and reaction kinetics. This NRM library is a compilation of the large body of knowledge on nutrient recovery processes that is currently available from research studies and operational experience. In addition to the development of a generic physicochemical modelling framework, a critical and challenging step when combining (stiff, i.e. numerical unstable) biological and physicochemical differential equations is their numerical solution (Lizarralde et al., 2015). Hence, a generic methodology to allow for accurate chemical speciation at minimal computational effort was also proposed.

Second, 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 a nutrient recovery treatment train, including methane and biogas production, digestate composition and pH, ammonium sulfate recovery, struvite production, product physicochemical purity (e.g., co-precipitation), particle size and density, air and chemical requirements (acid, base), scaling potential, etc. Model simulation outputs were found very sensitive to input waste stream characteristics through their direct effect on pH, which is adequately determined by means of the integrated chemical speciation calculation. Moreover, new data needs appeared, especially related to the physicochemical kinetic precipitation/dissolution and liquid-gas/gas-liquid transfer coefficients.

Based on the obtained generalizable insights, an optimal treatment train consisting of several unit processes was developed and assessed in terms of nutrient recovery performance and operating costs. Using model-based optimization the operating conditions and certain design variables have been optimized in view of maximized revenue at minimal environmental impact. It was revealed that the optimal configuration and associated operating conditions also depend on local legislations and fertilizer markets, next to the high influence of the input waste flow characteristics.

Based on all acquired knowledge, a generic roadmap for setting up nutrient recovery strategies as function of fertilizer markets, legislations and input flow characteristics was developed. It includes:

1. An overview of bio-based fertilization recommendations as function of fertilizer legislations;
2. Guidelines for determining the feasibility of nutrient recovery based on operational experience;
3. An algorithm for configuration and optimization of nutrient recovery treatment trains as function of input waste characterization and fertilizer markets.

RESULTS AND DISCUSSION

The global sensitivity analyses (GSA) provided important generic insights in the interactions between process inputs and outputs for the three different waste streams studied so far, i.e. sewage sludge, manure and a co-digestion mixture. For all unit processes, variations related to the input waste composition resulted in major effects on the output variation through their direct effect on the operational pH and ionic strength. Major findings involve, among others, the impact of chloride (Cl) inhibition on ammonia removal in the stripping unit (so, MgO or $Mg(OH)_2$ is to be preferred over $MgCl_2$:$6H_2O$ when applying preceding phosphorus (P) precipitation), the impact of calcium (Ca), iron (Fe) and aluminium (Al) inhibition on P recovery in the precipitation unit (suggesting the inclusion of a Ca/Fe/Al precipitate separator after the anaerobic digester), and 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 a subsequent ammonia stripper and thus reduces the need for base addition. Finally, if struvite is to be recovered, the implementation of the precipitation unit after digestion is also beneficial as the GSA showed that higher temperatures increase struvite purity.

Based on the results, it was possible to propose an optimal generic treatment train configuration for nutrient recovery aiming at the production of high-quality fertilizers (including struvite and AmS) at minimal cost (Figure 1).

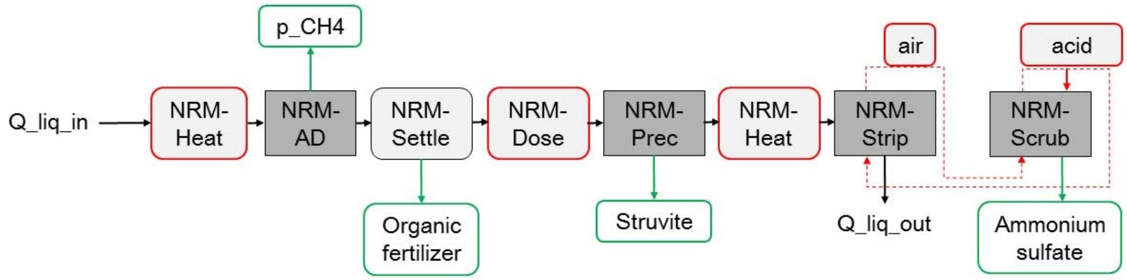

Figure 1 Proposed treatment train configuration targeting struvite and ammonium sulfate fertilizer; red = consumable (= cost); green = recovered resource (= revenue). AD = anaerobic digestion; Dose = chemical dosing; Heat = heat exchanger; Prec = precipitation/crystallization; p = partial pressure in the biogas; Q_liq = liquid flow rate; Scrub = scrubber; Strip = stripper.

Two important factors determining the optimal treatment train configuration for nutrient recovery are i) (local/regional) fertilizer legislations and markets, and ii) input characteristics of the waste flow (digestate in this case) to be treated (see above). A three-step roadmap for setting up nutrient recovery strategies as function of these determining factors is presented and discussed below.

Step 1: Set-up bio-based fertilization strategy as function of fertilizer legislations

If one wants to install a nutrient recovery treatment train, first contact should be sought with local/regional agronomic agencies and/or consultants in order to obtain insights in fertilizer related legislation 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. Overall, based on the analysis performed in this study, 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, among the considered recycled products, the most interesting fertilizers for agricultural purposes are the liquid fraction of digestate (as base fertilizer, whether or not mixed with raw digestate) and AmS.

Step 2: Evaluate feasibility of bio-based fertilizer production as function of input waste characterization

An important point to consider when designing nutrient recovery is the physicochemical characterization of the input waste stream to be treated. Obviously, first the macronutrients, especially N and P, of the waste flow have to be measured in order to check whether there is effectively an interest for N and P recovery. As such, technology providers confirmed that P recovery is only of interest if the P-load is higher than 80 kg d^{-1}, whereas N recovery using air stripping and scrubbing only becomes economically feasible at concentrations in the range of 400-500 mg N L^{-1}. Moreover, struvite production is only of interest if the waste flow has an N:P molar ratio above 1. The optimal N:P-ratio to maximize struvite recovery and purity would be higher than 6. Below that ratio, significant co-precipitation (e.g., with Ca-P) is to be expected. If, based on the above measurements, 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 of conceptual algorithm for treatment train configuration and optimization

A conceptual algorithm was developed on the basis of the findings in this research and contact with technology providers. It gives an overview of guidelines for configuration of nutrient recovery treatment trains, taking in account input waste characteristics and fertilizer market demands. The following digestate treatment train configurations depending on the feasibility scenario were identified:

1. *N and P recovery not feasible:* No action should be taken;
2. *P recovery not feasible, N recovery feasible:* The recommended treatment train configuration concerns NH_3 stripping and acidic air scrubbing (after anaerobic digestion), with optional pre- and post-treatments, depending on the nature of the waste material;
3. *P recovery feasible, N recovery feasible or not feasible + market for struvite available at acceptable transportation costs:* The recommended treatment train configuration concerns struvite precipitation, followed by AmS recovery (depending on the N content);
4. *P recovery feasible, N recovery feasible or not feasible + N:P-ratio and/or fertilizer markets not favourable for struvite recovery:*
    a. Digestate produced via thermophilic digestion: The recommended treatment train configuration concerns AmS recovery (depending on the N content), followed by Ca/Mg-P precipitation;
    b. Digestate produced via mesophilic or psychrophilic digestion: The recommended treatment train configuration concerns Ca/Mg-P precipitation, followed by AmS recovery (depending on the N content).

CONCLUSIONS

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

1. An overview of bio-based fertilization recommendations as function of fertilizer legislations;

2. Guidelines for determining the feasibility of nutrient recovery based on operational experience;

3. An algorithm for configuration and optimization of nutrient recovery treatment trains as function of input waste characterization and fertilizer markets.

As such, this paper provides useful guidance for wastewater and residuals processing utilities considering the implementation of nutrient recovery practices.

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