Waste Management 78 (2018) 385–392

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

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

Céline Vaneeckhaute [a,d,e,*], Evangelina Belia [b], Erik Meers [c], Filip M.G. Tack [c], Peter A. Vanrolleghem [d,e]

[a] BioEngine – Research Team on Green Process Engineering and Biorefineries, Chemical Engineering Department, Université Laval, 1065 ave. de la Médecine, Québec, QC G1V 0A6, Canada
[b] Primodal Inc., 145 Rue Aberdeen, Québec, QC G1R 2C9, Canada
[c] EcoChem, Laboratory of Applied Ecochemistry, Ghent University, Coupure Links 653, Ghent 9000, Belgium
[d] modelEAU, Département de génie civil et de génie des eaux, Université Laval, 1065 ave. de la Médecine, Québec, QC G1V 0A6, Canada
[e] CentrEau, Centre de recherche sur l'eau, Université Laval, 1065 avenue de la Médecine, Québec, QC, G1V 0A6, Canada

ARTICLE INFO

Article history:
Received 1 June 2017
Revised 19 April 2018
Accepted 24 May 2018

Keywords:
Anaerobic digestion
Bio-based fertilizers
Decision-support
Nutrient recycling
Resource recovery
Struvite

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.

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, $MgNH_4PO_4{:}6H_2O$, 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

* Corresponding author.
E-mail addresses: celine.vaneeckhaute@gch.ulaval.ca (C. Vaneeckhaute), belia@primodal.com (E. Belia), erik.meers@ugent.be (E. Meers), filip.tack@ugent.be (F.M.G. Tack), peter.vanrolleghem@gci.ulaval.ca (P.A. Vanrolleghem).

https://doi.org/10.1016/j.wasman.2018.05.047
0956-053X/

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 co-digestion 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 $MgCl_2{:}6H_2O$ 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 decision-support 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 decision-support 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), NH_3 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 guideline-based 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 NH_3 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 bio-fertilizer characteristics, and regulatory data, such as maximum nutrient application standards. Such data were obtained through