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Economic Optimization of Integrated Nutrient and Energy Recovery Treatment Trains Using a New Model Library

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Abstract

In order to hasten the implementation of optimal, cost-effective, and sustainable treatment trains for resource recovery, a nutrient recovery model (NRM) library has been developed and validated at steady state. The reported research aims to use the NRM library to establish the operational settings of a sustainable and cost-effective treatment scenario with maximal resource recovery and minimal energy and chemical requirements. Under the optimized conditions and assumptions made, potential financial benefits for a large-scale anaerobic digestion and nutrient recovery project were estimated at 2.8-6.5 USD m^{-3} manure based on net variable cost calculations, or an average of ± 2 USD m^{-3} y^{-1}, equivalent with 40 USD t^{-1} total solids y^{-1}, over 20 years in the best case when also taking into account capital costs. Hence, it is likely that in practice a full-scale ZeroCostWRRF (water resource recovery facility at zero cost) can be constructed.

Keywords: anaerobic digestion; circular economy; mathematical modelling; process optimization; resource recovery

1. Introduction

To hasten the implementation and integration of sustainable nutrient recovery strategies and to adequately put together an optimal treatment train of unit processes for resource recovery, a generic nutrient recovery model (NRM) library has recently been developed and validated at steady state (Vaneeckhaute et al., 2018). The proposed models are dynamic mathematical models, based on detailed solution speciation and reaction kinetics. Key unit process models were developed for anaerobic digestion (NRM-AD), phosphorus precipitation/crystallization (NRM-Prec), nitrogen stripping (NRM-Strip) and absorption using an acidic air scrubber (NRM-Scrub). In view of simulating complete treatment trains for nutrient and energy recovery, also ancillary unit process models for solid-liquid separation (NRM-Settle), chemical dosing (NRM-Chem) and a heating unit (NRM-Heat) were built. To facilitate numerical solution, a highly efficient interface between the geochemical modelling software PHREEQC and the water quality modelling software WEST (DHI) was established and verified. Global sensitivity analyses (GSA) were performed in order to define the most important factors impacting a wide range of 25 performance indicators of a nutrient and energy recovery treatment train, such as methane and biogas production, digestate composition and pH, ammonium sulfate recovery, struvite production, product particle size and density, and air and chemical (acid, base) requirements (Vaneeckhaute et al., 2015).

Model simulation outputs were very sensitive to input waste stream characteristics through their direct effect on pH, which is adequately determined by means of the chemical speciation calculation integrated in the process models. Moreover, important generic insights in the interactions between process inputs and outputs were obtained through GSA (Vaneeckhaute et al., 2015). Based on the results, it was possible to define an optimal sequence of unit processes in a treatment train for energy and nutrient recovery aiming at the production of high-quality fertilizers at minimal cost (Figure 1).

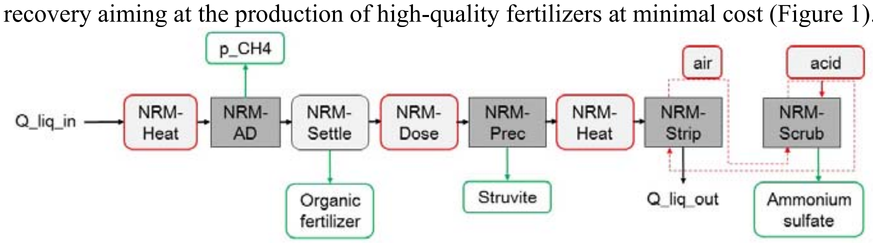

Figure 1 Optimal treatment train configuration targeting bio-based struvite and ammonium sulfate fertilizer production; Red = consumable (= cost); Green = recovered resource (= revenue); AD = anaerobic digestion; Dose = chemical dosing; Heat = heat exchanger; Prec = precipitation/crystallization; p =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

This paper aims to present the use of the NRM library to establish the operational settings of a sustainable and cost-effective treatment scenario with maximal resource recovery and minimal energy and chemical requirements. To this end, an economic analysis was programmed in the process model library, and the operational settings of the above treatment train (Figure 1) were optimized for pig manure as a case study.

2. Methodology

First, realistic design parameters for the unit processes in the nutrient recovery treatment train (Figure 1) were obtained by distributing a technical questionnaire to key technology suppliers in the field. A cost estimate for a design flow of 2,000 m^3 d^{-1} as input to the anaerobic digester was requested using input ranges for nitrogen (N), phosphorus (P), chemical oxygen demand (COD), volatile suspended solids (VSS), total solids (TS), and alkalinity from Cesur and Albertson (2005). The resulting digestate composition (Cesur and Albertson, 2005) was used as input to the nutrient recovery units. Based on the data obtained from the budget proposals, the operational envelope for optimization was compiled. It includes: i) the operational temperature, liquid flow rate, and amount of base/alkalinity dosing for the anaerobic digester, ii) the fraction of non-settleable precipitates and particulate COD for the phase separation unit, iii) the amount of base dosing, the concentration of seed material in the input flow, and precipitate extraction rate for the precipitation unit, iv) the operational temperature and gas flow rate for the stripping unit, and v) the acid dose and liquid recycle flow rate for the scrubbing unit. The initial values for the optimization experiment were set at the design values provided by the technology providers. The lower and upper limits were set at the values for the unit process GSAs defined in Vaneeckhaute (2015).

The key performance indicators evaluated in the optimization experiment were:

i. **Net costs = chemical costs + energy costs – revenues** (objective = minimize), where:
    a. energy cost items are related to raising the liquid temperature for anaerobic digestion and stripping (with potential for heat exchange, see below), as well as to air pumping for stripping;
    b. chemical cost items refer to the addition of alkalinity or base to the digester, of acid for N absorption in the scrubber, and of base for pH-increase prior to precipitation and stripping;
    c. revenues are related to CH_4 production (energy recovery was assumed, see below), the marketing of mineral fertilizer N, P, and potassium (K), and the potential marketing of organic fertilizer.
ii. **Resource recovery** (objective = maximize), which includes:
    a. methane recovery in NRM-AD;
    b. mineral N, P, and K recovery in NRM-Prec;
    c. mineral N and sulfur (S) recovery in NRM-Strip/NRM-Scrub;
    d. organic (+ N/P/K) fertilizer recovery (settled solids) in NRM-Settle.
iii. **Use of consumables** (objective = minimize), involving:
    a. net thermal energy use = heat required for stripping + heat required for digestion – heat recovered from CH_4 production – potential heat recovered in heat exchangers (see below);
    b. net electricity use = blower energy (air) – electricity recovered from CH_4 production;
    c. chemical use = acid use + base/alkalinity use.

Biogas CH_4 was assumed to be valorized as energy in a combined heat and power generation (CHP) unit, with a conversion efficiency of 40 % as heat, 38 % as electricity, and assuming 22 % heat losses. In terms of heat requirements, both a worst and best-case scenario was considered. In the best case, 10 % heat losses in the digester and 50 % internal heat recovery in the stripping system were assumed as indicated by technology providers. In the worst case, the heat requirements in the digester were 1.9 times higher than the theoretical heat required to heat the input flow. In that case, no internal heat recovery in the stripping system was considered.

To perform the calculations, the GN_Direct algorithm, i.e. DIviding RECTangles algorithm for global optimization (Gablonsky and Kelley, 2001), available from the

NLOpt solver package in WEST, was used with a tolerance of 10^{-8} and a maximum of 10,000 evaluations. The operational envelope of the treatment train was optimized, after which a detailed economic analysis for the treatment train with optimized operational settings was performed, including all operational costs, labor, material and maintenance costs, revenues from CO_2-emission reduction credits, as well as capital costs.

3. Results and Discussion

The optimized values of the operational factors considered in the optimization experiment are compiled in Table 1. Key performance indicators that were calculated using the optimized factors are also provided. An overview of the annual treatment train operational costs and revenues under the optimized conditions, as well as the capital costs for each unit process in the treatment train is presented in Table 2. The estimation is based on an operational basis of 8,000 hours per year. All costs are expressed in USD.

As depreciation costs and loan service costs vary depending on when and where the money is borrowed, stakeholders are interested in the **yearly net cash flows** determined by the variable costs and revenues. Based on the optimized values obtained and all assumptions made in this case study, the yearly net variable cost balance can be positive. Financial benefits could even be obtained, estimated at about 2.8-6.5 \$ m^{-3} manure y^{-1} (55-130 \$ t^{-1} TS^{-1} y^{-1}) for the large-scale project and associated assumptions in this case. Hence, in terms of net variable cash flows, it is likely that in practice a ZeroCostWRRF (water resource recovery facility at zero cost) could be achieved. As one could be critical on the optimized (low) digester temperature and hydraulic residence time (HRT) obtained in this study (Table 1), the economic analysis was also performed for a digester operated at a temperature of 50 °C with a HRT of 15 d. The financial benefits in this scenario amounted to 2-6 \$ m^{-3} manure y^{-1}, which is competitive with the above optimal scenario. Hence, if a high-temperature treatment is required for end-product pasteurisation, the latter scenario may be targeted, though it is less sustainable in terms of consumables (heat and chemical use). At a HRT of 30 days, the financial benefits amounted to about 3 \$ m^{-3} y^{-1} in the best case, but a loss of 1.5 \$ m^{-3} y^{-1} was obtained in the worst case. The most important factor impacting the operational cost balance, next to the HRT, is the potential for heat recovery. Hence, process and design engineers should focus on the optimization of heat balances in the configuration of future integrated nutrient and energy recovery facilities.

Furthermore, when considering capital costs, stakeholders may be interested in the **net present value** (NPV), which is the sum of the present values of incoming and outgoing cash flows over a period of time, including the investment cost at time 0. Assuming an average discount rate of 6 % and a depreciation period of 20 years for all unit processes, except for the stripping unit, for which a depreciation period of eight years was assumed as advised by technology providers, the nutrient recovery project presented above would have a positive NPV in year 7 of operation in the best case. This value is at the lower end of the range of payback times for existing anaerobic digestion plants without a nutrient recovery treatment train in the US, i.e. 6.9-8.9 years based on a survey of 24 plants (Vik, 2003). The NPV after 20 years amounted to about 3.5 M \$, resulting in average net financial benefits of ± 2 \$ m^{-3} manure y^{-1} (40 \$ t^{-1} TS y^{-1}) over 20 years.

Table 1 Value of the optimized factors in the treatment train optimization experiment and of the resulting performance indicators; Underlined values impact costs, while italicized values impact revenues; COD = chemical oxygen demand; f_ns_P = fraction of non-settleable precipitates; f_ns_X = fraction of non-settleable biological particulate solids.

	OPTIMIZATION		PERFORMANCE	
Unit process	**Optimized factor**	**Value**	**Indicator**	**Value**
Anaerobic digester	Temperature (°C)	28	Heat input (best/worst case; MWh_{th} d^{-1})	24-41
	Flow rate (m^3 d^{-1})	2,700	HRT (d)	15
	Ca-dose (kg d^{-1})	0	*COD degradation (%)*	55
			VSS degradation (%)	45
			CH_4 production (m^3 m^{-3} manure)	5.8-7.4
			Heat recovery (MWh_{th} d^{-1})	72
			Electricity recovery (MWh_{el} d^{-1})	68
Phase separation	f_ns_P	0.25	*Organic fertilizer production (ton X_COD d^{-1})*	15
	f_ns_X	0.05		
Precipitation unit	$Mg(OH)_2$ dose (ton d^{-1})	1.5	*Mineral fertilizer production (ton P d^{-1})*	1.5
	Seeding Kstruvite (g m^{-3})	3.1	*P recovery (%)*	99
	Seeding Struvite (g m^{-3})	3.1		
	Precipitate flow rate (m^3 d^{-1})	150		
Stripper	Temperature (°C)	55	Heat input (best/worst case; MWh_{th} d^{-1})	42-85
	Gas flow rate (Mm^3 d^{-1})	1.5	Electricity input (MWh_{el} d^{-1})	2.9
	Gas pressure (atm)	4		
Scrubber	Acid flow rate (m^3 d^{-1})	17.5	*Mineral fertilizer production (ton N d^{-1})*	5.0
	Liquid recycle rate (m^3 d^{-1})	2.5	*NH_4-N recovery (%)*	84

Table 2 Costs and revenues (k$ y^{-1}) for the optimized nutrient recovery treatment train; $ = USD; AD = anaerobic digester; CHP = conventional heat and power; CAPEX = capital expenditures; OPEX = operational expenditures.

COSTS (k$ y^{-1})	FIXED COSTS	VARIABLE COSTS					REVENUES RESOURCE RECOVERY		
		OPEX				Maintenance, material & labor	Biogas + fertilizer	Biogas + fertilizer	CO_2 credits
UNIT	CAPEX	Heat (best)	Heat (worst)	Electricity	Chemicals		best	worst	
AD + CHP	22,5	694	1,198	621	-	977	3,547	3,547	1,334
Phase separation	1,25	-	-	2.5	to be evaluated	226	1,741	0	-
Precipitation	4,75	-	-	6.3	102	48	1,468	1,468	-
Strip/Scrub	680	1,034	2,069	74	913	6.8	2,365	2,365	-
Other	2	-	-	-	-	-	-	-	-
Rounded total	**31**	**1,75**	**3,25**	**700**	**1**	**1,25**	**9,1**	**7,4**	**1,35**

The **internal rate of return** (IRR), i.e. the discount rate that makes the NPV equal to zero, after 20 years in this case was 18 %, which approximates the estimated best-case IRR (including subsidies) after 20 years for an operational full-scale WRRF in the Netherlands, i.e. 19-21 % (Gebrezgabher et al., 2010). In the worst-case scenario, the IRR after 20 years was only 5 %. Hence, based on the analysis (worst vs. best case), it can be stated that the feasibility of implementing a resource recovery project will highly depend on the heat recovery potential, the marketing potential of the fertilizers, as well as the subsidies obtained. For instance, when accounting for an income of 40 $ t^{-1} net saved CO_2-equivalents (= current global market price of carbon; LLC, 2012) instead of the conservative US carbon prices (15 \$ t^{-1} CO_2-equivalents), the IRR would be around 26 % and 14 % in the best and worst case, respectively, resulting in a revenue of 1.3-3.4 \$ m^{-3} manure y^{-1} (25-70 \$ t^{-1} TS y^{-1}) averaged over 20 years.

4. Conclusions

The potential of the NRM library for optimization of the operational settings of a selected nutrient and energy recovery treatment train was presented by means of a case study for pig manure. An economic analysis indicated that in the best-case scenario a ZeroCostWRRF can be constructed. The NPV after 20 years amounted to about 3.5 M USD, resulting in average net financial benefits of ± 2 USD m^{-3} manure y^{-1} or 40 USD t^{-1} total solids y^{-1} over 20 years. The IRR after 20 years was 18 %. Results indicate that subsidies, fertilizer marketing potential and heat balances are key factors determining the feasibility of resource recovery projects. Hence, process and design engineers should focus on the optimization of heat balances in the configuration of future integrated nutrient and energy recovery facilities. Fertilizer regulations and subsidies should be adjusted accordingly.

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