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Model-based optimisation and economic analysis to quantify the viability and profitability of an integrated nutrient and energy recovery treatment train

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In order to hasten the implementation of optimal, cost-effective and sustainable treatment trains for resource recovery from biowaste, a new nutrient recovery model (NRM) library has been developed and validated at steady state. It includes physico-biochemical mathematical models for anaerobic digestion, struvite precipitation and ammonia stripping and absorption as ammonium sulfate. The present paper describes the use of the NRM library to establish the operational settings of a sustainable and cost-effective treatment scenario with maximal resource (nutrients and biogas) recovery and minimal energy and chemical requirements. Under the optimised conditions and assumptions made, potential financial benefits for a large-scale anaerobic digestion and nutrient recovery project treating 2700 m^3/d of pig manure were estimated at US\$2·8–6·5/m^3 based on net variable cost calculations, or an average of ~\$2/(m^3 year), equivalent to \$40/(t total solids year), over 20 years in the best case when also taking into account capital costs. Hence, it is likely that in practice a full-scale zero-cost biorefinery for nutrient and energy recovery from manure can be constructed. As such, this paper demonstrates the potential of the NRM library to facilitate the implementation of sustainable nutrient and energy (biogas) recovery treatment trains for biowaste valorisation.

Notation

i	discount rate (i.e. the rate of return that could be earned on an investment in the financial markets with similar risk)
N	total number of periods (years)
R_t	net cash flow (i.e. cash inflow – cash outflow) at time t
t	time of the cash flow

Introduction

Medium- (2020) and long-term (2050) strategic environmental policy objectives are set across the world in order to support the growth of a more innovative, resource-efficient economy, based on the sustainable production of biobased products (bioenergy and biomaterials) from renewable biomass sources (BENC, 2015; EuropaBio, 2015; UNEP, 2013). In the framework of these objectives, the anaerobic (co-)digestion of sewage sludge, organic biological food waste and animal manure has been evaluated as one of the most energy-efficient and environmentally friendly technologies for bioenergy production, organic biodegradable waste valorisation and potential recovery of valuable nutrient resources, which are concentrated in the remaining mineralised digestate (UNEP, 2013; Vaneeckhaute *et al.*, 2017). Despite its great potential, the further sustainable development of this technology is currently hindered, because these digestates can often not or only sparingly be returned to agricultural land in their crude unprocessed form. This is particularly the case in high-nutrient regions, such as (parts of) Western Europe (e.g. Flanders (Belgium), the Netherlands, Nordrhein-Westfalen (Germany), Bretagne (France) and Denmark), the Eastern and Midwestern USA and Canada (e.g. Québec, Alberta, Ontario, Pennsylvania and California) and areas of East and South Asia, due to strict regulatory constraints related to the surplus production of animal manure in comparison to the available arable land to spread it on (FAO, 2004). Moreover, in most countries, periods when spreading fertiliser on agricultural land is allowed are regulated in order to minimise nutrient leaching. Therefore, the storage capacity for digestate becomes expensive due to its large volume, and transportation problems may occur during application periods. Hence, further processing of digestate into transportable/exportable end products, concentrated mineral fertilisers (chemical fertiliser substitutes) and/or environmentally neutral components is required to overcome practical and potential environmental problems, as well as regulatory bottlenecks related to the direct application of digestate.

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So far, the technical approach for digestate processing was similar to the approach for the treatment of manure and waste water. As such, energy-intensive and little cost-effective technologies for nutrient removal (i.e. destruction or emission) have mainly been used such as biological nitrification/denitrification. The challenge for anaerobic digestion plants now is to achieve optimal recovery and recycling of nutrients from the digestate in a sustainable way. As such, regulatory drivers can be met and an internal revenue source can be produced – that is, the present 'waste' problem can be turned into an economic opportunity (Vaneeckhaute *et al.*, 2013).

Over the past decade, several industrial technologies for nutrient recovery as biofertiliser have been proposed and implemented at pilot or full scale, among which struvite precipitation and ammonia (NH_3) stripping and absorption as ammonium sulfate are the most common implemented technologies to date (Vaneeckhaute *et al.*, 2017). However, challenges remain in improving the operational performance, decreasing the economic costs and recovering the nutrients as marketable products with added value for the chemical or agricultural sector. 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 also key concerns.

Mathematical models provide useful tools for optimisation of waste and waste water treatment plants in a time- and cost-efficient way. However, the current available models for anaerobic digestion are limited due to the omission of key fundamental physico-chemical components and transformations that are essential for describing nutrient recovery unit processes (Batstone *et al.*, 2012; Brouckaert *et al.*, 2010; Flores-Alsina *et al.*, 2015). Hence, at the start of this research, no complete model library including anaerobic digestion and nutrient recovery processes was available. As such, the potential to simulate and optimise complete treatment trains for both nutrient and energy recovery from digestate was absent.

To fill this gap in modelling potential, Vaneeckhaute *et al.* (2018a) recently developed and validated a generic nutrient recovery model (NRM) library. Key unit process models were developed for anaerobic digestion (NRM-AD), phosphorus (P) precipitation/crystallisation as struvite (NRM-Prec), nitrogen (N) stripping (NRM-Strip) and absorption as ammonium sulfate using an acidic air scrubber (NRM-Scrub). The proposed models are dynamic mathematical models, based on detailed chemical solution speciation and reaction kinetics.

In view of simulating complete treatment trains for nutrient and energy recovery, ancillary unit process models for solid–liquid separation (NRM-Settle), chemical dosing (NRM-Chem) and a heating unit (NRM-Heat) were also built. To facilitate numerical solution, a highly efficient interface between the geochemical software Phreeqc (Charlton and Parkhurst, 2011) and WEST (https://www.dhigroup.com/; Vanhooren *et al.*, 2003) was established and verified. Global sensitivity analyses (GSAs) 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 (CH_4) 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.*, 2018b). As such, important generic insights in the interactions between process inputs and outputs were obtained (Vaneeckhaute *et al.*, 2018b). Based on the results, it was possible to define an optimal sequence of unit processes in a treatment train for nutrient and energy recovery aiming at the production of high-quality fertilisers at minimal cost (Figure 1).

The present paper aims to establish the operational settings of a sustainable and cost-effective treatment scenario with maximal resource (nutrients and biogas) recovery and minimal energy and chemical requirements using the NRM library. To this end, an economic analysis was programmed in the process model library, and the operational settings of the treatment train in Figure 1 were optimised for pig manure as a case study. A conceptual overview of the overall research strategy used is presented in Figure 2. Steps 1 to 4 are presented by Vaneeckhaute *et al.* (2018b) as described earlier. Starting from the defined treatment train configuration (Figure 1), this paper presents the use of the NRM library for technical and economic treatment train optimisation (steps 5 and 6). As such, this paper tackles the current lack in modelling potential – that is, to perform an optimisation and economic analysis of complete treatment trains for nutrient and energy recovery. Moreover, the paper brings forward the potential

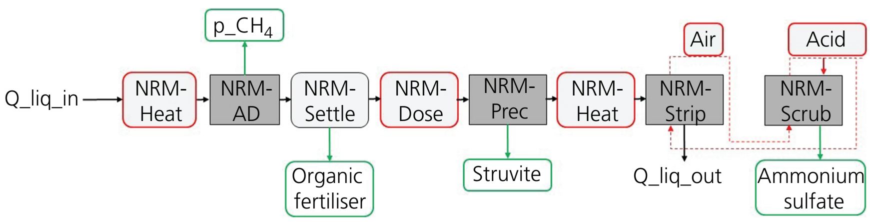

Figure 1. Optimal treatment train configuration targeting struvite and ammonium sulfate fertiliser. Red = consumable (= cost); green = recovered resource (= revenue). AD, anaerobic digestion; Dose, chemical dosing; Heat, heat exchanger; Prec, precipitation/crystallisation; p, partial pressure in the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

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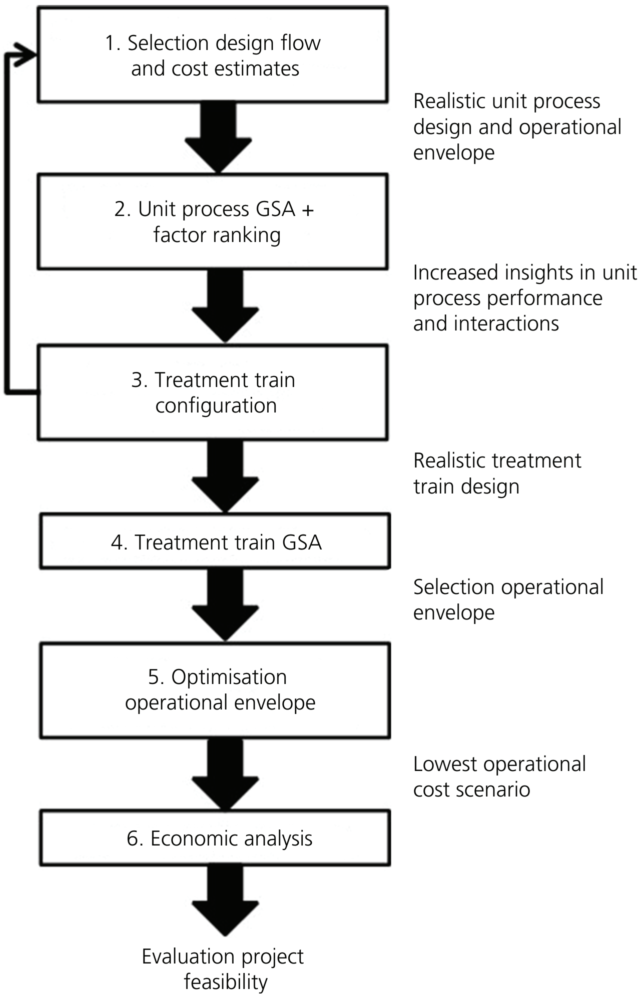

Figure 2. Conceptual overview: use of the NRM library for treatment train configuration and optimisation. GSA, global sensitivity analysis

of the newly developed NRM library to facilitate the implementation of sustainable nutrient and energy (biogas) recovery treatment trains for biowaste valorisation. The NRM library is freely available on request.

Methodology

Treatment train optimisation

The considered treatment train configuration for optimisation is presented in Figure 1. It concerns the following items in sequence: (*a*) a heating unit to heat up the input streams to the digester, (*b*) an anaerobic digestion unit producing biogas, (*c*) a solid–liquid phase separation unit producing an organic fertiliser, (*d*) a chemical dosing unit in order to adjust the pH and magnesium content for subsequent struvite precipitation, (*e*) a struvite precipitation/crystallisation unit, (*f*) a heating unit to heat up the input stream to the stripping unit, (*g*) a stripping unit to recover gaseous ammonia, (*h*) a scrubbing unit to absorb the gaseous ammonia as ammonium sulfate, (*i*) an acid-dosing unit to add sulfuric acid (H_2SO_4) for absorption and (*j*) an airflow that circulates between the stripper and the scrubber. Cost items are marked in red in Figure 1 and include the heating units (items (a) and (*f*)), the chemical dosing units (items (*d*) and (*i*)) as well as the airflow (item (*j*)). Revenues are marked in green in Figure 1 and include the produced biogas (related to item (*a*), the organic fertiliser (related to item (*c*)), the struvite (related to item (*e*)) and the ammonium sulfate (related to item (*h*)).

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 (three for anaerobic digestion, two for struvite precipitation and four for stripping and scrubbing). A cost estimate for a design flow of 2000 m^3/d as input to the anaerobic digester was requested using input ranges for nitrogen, phosphorus, chemical oxygen demand (COD), volatile suspended solids (VSS), total solids (TS) and alkalinity from the paper of Cesur and Albertson (2005). The resulting digestate composition

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Table 1. Design parameters for each key unit process in the NRM library

Key unit	Parameter	Symbol	Design value	Unit
NRM-AD	Liquid volume	V_liq	40 000[a]	m^3
NRM-AD	Gas volume	V_gas	3000[a]	m^3
NRM-Prec	Liquid volume	V_liq	500[a]	m^3
NRM-Strip/NRM-Scrub[b,c]	Reactor volume	V	80[a]	m^3
NRM-Strip/NRM-Scrub[b,c]	Reactor height	H	12	m

[a]Volume reflects the total capacity. It can be divided over different units, depending on the technology provider – for example, anaerobic digestion can be performed using four units of 10 000 m^3
[b]Values indicate reactor dimensions for the individual stripper and scrubber unit. Hence, both units have the same size
[c]At an operational temperature of 50–55°C, pH > 10, and gas/liquid ratio of ~800 m^3/m^3
AD, anaerobic digestion; Prec, precipitation/crystallisation; Scrub, scrubber; Strip, stripper

(Cesur and Albertson, 2005) was used as input to the nutrient recovery units. The results of this questionnaire are provided in Table 1.

A mesophilic (35°C) anaerobic digestion process was assumed. The design values for the stripper are based on an operational temperature of 50–55°C, a pH > 10 and a gas/liquid ratio of ~800 m^3/m^3.

Based on the data obtained from the budget proposals, the operational envelope for optimisation was compiled. It includes (Table 2) (*a*) the operational temperature, liquid flow rate and amount of base/alkalinity dosing for the anaerobic digester; (*b*) the fraction of non-settleable precipitates and particulate COD for the phase separation unit; (*c*) the amount of base dosing, the concentration of seed material in the input flow and precipitate extraction rate for the precipitation unit; (*d*) the operational temperature and gas flow rate for the stripping unit; and (*e*) the acid dose and liquid recycle flow rate for the scrubbing unit. The initial values for the optimisation experiment were set at the design values given in the budget proposals provided by the technology providers (Table 2). The lower and upper limits were set at the values for the unit process GSAs defined by Vaneeckhaute *et al*. (2018b).

The key performance indicators evaluated in the optimisation experiment were the following.

(*a*) Net costs = chemical costs + energy costs − revenues (objective = minimise), where
  (*i*) energy cost items are related to raising the liquid temperature for anaerobic digestion and stripping (with potential for heat exchange, see later), as well as to air pumping for stripping
  (*ii*) chemical cost items refer to the addition of alkalinity or base to the digester, of acid for nitrogen absorption in the scrubber and of base for pH increase prior to precipitation and stripping
  (*iii*) revenues are related to methane production (energy recovery was assumed, see later); the marketing of mineral fertilisers nitrogen, phosphorus and potassium (K); and the potential marketing of organic fertiliser.
(*b*) Resource recovery (objective = maximise), which includes
  (*i*) methane recovery in NRM-AD
  (*ii*) mineral nitrogen/phosphorus/potassium recovery in NRM-Prec
  (*iii*) mineral nitrogen/sulfur (S) recovery in NRM-Strip/NRM-Scrub
  (*iv*) organic (+ nitrogen/phosphorus/potassium) fertiliser recovery (settled solids) in NRM-Settle.

Table 2. Lower and upper limits and initial value used for each factor in the treatment train optimisation experiment

Model	Symbol	Description	Lower	Upper	Initial	Unit
NRM-Heat 1	Temp_Target_AD	Target digester temperature	20	55	35	°C
NRM-AD	Q_liq_in	Liquid flow rate	1000	3000	2000	m^3/d
NRM-AD	S_Ca	Calcium dose	42	300	92	mol/m^3
NRM-Settle	f_ns_P	Fraction of non-settleable precipitates	0	0·5	0·1	—
NRM-Settle	f_ns_X	Fraction of non-settleable solids	0	0·1	0·005	—
NRM-Dose	$Mg(OH)_2$_dose	Magnesium hydroxide dose	0	3000	1500	kg/d
NRM-Prec	S_Seed_KStruvite	Seed material for K-struvite precipitation	0·0001 25	6·25	0·001	g/m^3
NRM-Prec	S_Seed_Struvite	Seed material for struvite precipitation	0·0001 25	6·25	0·001	g/m^3
NRM-Prec	Q_prec	Precipitate extraction rate	1	300	30	m^3/d
NRM-Strip	Q_gas_in	Gas flow rate	1 000 000	2 000 000	1 600 000	m^3/d
NRM-Strip	P_gas_in	Gas pressure	1	7	2·4	atm
NRM-Heat 2	Temp_Target_Strip	Target stripping temperature	40	70	55	°C
NRM-Scrub	Q_liq_in (acid)	Acid flow rate	5	30	11	m^3/d
NRM-Scrub	Q_recycle	Liquid recycle flow rate	0	5	2	m^3/d

AD, anaerobic digestion; Prec, precipitation/crystallisation; Scrub, scrubber; Strip, stripper

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(*c*) Use of consumables (objective = minimise), involving
   (*i*) net thermal energy use = heat required for stripping + heat required for digestion − heat recovered from methane production − potential heat recovered in heat exchangers (see later)
   (*ii*) net electricity use = blower energy (air) − electricity recovered from methane production
   (*iii*) chemical use = acid use + base/alkalinity use.

An overview of the parameters used in the energy and cost calculations is given in Table 3. Costs are expressed in US dollars.

Biogas methane was assumed to be valorised as energy in a combined heat and power generation (CHP) unit, with a conversion efficiency of 40% as heat and 38% as electricity and assuming 22% heat losses (Verstraete and Vlaeminck, 2011). In terms of heat requirements, both a worst- and a best-case scenario were considered. In the best case, 10% heat losses in the digester (Wu and Bibeau, 2010; Zupancic and Ros, 2003) 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 (LAWPCA, 2009; Symantec, 2014; Tchobanoglous *et al*., 2003; Vaneeckhaute, 2009). In this case, no internal heat recovery in the stripping system was considered.

To perform the calculations, the GN_Direct algorithm – that is, the DIviding RECTangles algorithm for global optimisation (Gablonsky and Kelley, 2001; Jones *et al*., 1993), available from the NLOpt solver package (Johnson, 2008) included in WEST, was used with a tolerance of 10^{-8} and a maximum of 10 000 evaluations. This is the generally used algorithm in WEST for this type of complex optimisation problems. It concerns a deterministic-search algorithm based on systematic division of the search domain into smaller and smaller hyper rectangles. In the first step, only major factors (Table 3) were included in the cost and energy calculations for optimisation. In the second step, an overall detailed economic analysis (Figure 2: step 6) for the treatment train with optimised operational settings was performed, including additional operational costs, labour, material and maintenance costs, revenues from carbon dioxide (CO_2) emission reduction credits, as well as capital costs (see the next section).

Detailed economic analysis

In this study, the capital costs including equipment and construction costs for each unit process were obtained from the same technology providers who delivered the design reactor dimensions for the treatment train set-up (Table 1). When possible, the values were compared with values obtained from simulations with the software Capdet (Computer Assisted Procedure for the Design and Evaluation of Wastewater Treatment Systems) (Symantec, 2014; USEPA, 1981) to ensure that the obtained costs are realistic. The complete treatment train was also implemented in Capdet in order to estimate other important direct and indirect construction costs, not included in the unit process cost estimations, such as land costs (agricultural land was assumed), legal costs, inspection costs, costs of laboratory and administration buildings and miscellaneous costs (Symantec, 2014; USEPA, 1981). For the nutrient recovery systems that are not yet available in Capdet, user-defined unit processes were implemented using the specifications (capital costs, dimensions etc.) obtained from the technology providers.

Operational costs in terms of heat and chemical consumption were calculated from the derived optimised factors (see results in Table 4, underlined values). For the heat requirements, both a worst- and a best-case scenario were considered, as described earlier. In each scenario, an average input manure temperature of 20°C was supposed, similar as, for example, in the Capdet software and in the paper of Khiewwijit *et al*. (2015). The final effluent leaves the stripper at 25°C, as indicated by the technology providers. Hence, the temperature difference between the final effluent and the input manure to the digester is in this case too small for heat recovery between these flows.

Table 3. Parameters used to calculate energy and cost functions in the virtual optimisation experiment

Category	Item	Value	Unit	Reference
Chemical cost	Sulfuric acid (98%)	0·087	\$/kg	Icis (2014)
	Magnesium hydroxide	0·204	\$/kg	Icis (2014)
	Magnesium chloride hexahydrate (99%)	0·066	\$/kg	Icis (2014)
	Calcium hydroxide	0·070	\$/kg	Icis (2014)
	Sodium hydroxide (100%)	0·635	\$/kg	Icis (2014)
Energy cost	Electricity	0·076	\$/kWh	USEPA (2013)
Energetic value	Air (strip)[a]	0·00195	kWh/m^3 air	RVTPE (2014)
	Methane[b]	13·9	kWh/kg	Tchobanoglous *et al*. (2003)
	Heat capacity sludge/manure	4·2	kJ/(kg °C)	Tchobanoglous *et al*. (2003)
Nutrient value	Nitrogen	1·411	\$/kg	USEPA (2013)
	Phosphorus	2·984	\$/kg	USEPA (2013)
	Potassium	0·960	\$/kg	USEPA (2013)

[a]Internal air recycling between the stripper and scrubber system is assumed (RVTPE, 2014)
[b]Density of methane at 25°C = 0·656 kg/m^3 (Tchobanoglous *et al*., 2003)

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Table 4. Values of the optimised factors in the treatment train optimisation experiment and of the resulting performance indicators

Unit process	Optimisation		Performance	
	Optimised factor	Value	Indicator	Value
Anaerobic digester	Temperature: °C	28	**Heat input (best/worst case):[a] MWh_{th}/d**	24–41
	Flow rate: m^3/d	2700	Hydraulic retention time: d	15
	Calcium dose: kg/d	0	*COD degradation: %*	55
			VSS degradation: %	45
			Methane production: m^3/m^3 manure	5·8–7·4[b]
			Heat recovery:[c] MWh_{th}/d	72
			Electricity recovery:[c] MWh_{el}/d	68
Phase separation	f_ns_P	0·25	*Organic fertiliser production:[d] t X_COD/d*	15
	f_ns_X	0·05		
Precipitation unit	**Magnesium hydroxide dose: ton/d**	1·5	*Mineral fertiliser production:[e] t phosphorus/d*	1·5
	Seeding K-struvite: g/m^3	3·1	*Phosphorus recovery:[e] %*	99
	Seeding struvite: g/m^3	3·1		
	Precipitate flow rate: m^3/d	150		
Stripper	Temperature: °C	55	**Heat input: best/worst case; MWh_{th}/d[f]**	42–85
	Gas flow rate: Mm^3/d	1·5	**Electricity input: MWh_{el}/d**	2·9
	Gas pressure: atm	4		
Scrubber	**Acid flow rate: m^3/d**	17·5[g]	*Mineral fertiliser production:[h] t nitrogen/d*	5·0
	Liquid recycle rate: m^3/d	2·5	*NH_4-nitrogen recovery:[h] %*	84

[a]Best case: 10% heat losses (Wu and Bibeau, 2010; Zupancic and Ros, 2003). Worst case: heat requirement that is 1·9 times higher than the theoretical heat required for manure heating (LAWPCA, 2009; Tchobanoglous *et al*., 2003; USEPA, 1981; Vaneeckhaute, 2009). Waste input temperature: 20°C (Khiewwijit *et al*., 2015; USEPA, 1981)
[b]First number: considering 22% methane losses (see below); second number: not accounting for methane losses
[c]Conversion of methane in a conventional heat and power system: 40% thermal energy, 38% electricity, 22% losses (Verstraete and Vlaeminck, 2011)
[d]Recovered as digested solids (particulate COD + calcium, iron and aluminium precipitates) in NRM-Settle
[e]Recovered as magnesium–phosphorus fertiliser. % recovery was calculated from soluble phosphorus that enters the NRM-Prec unit. The same maximal % recovery was found by Ye *et al*. (2010)
[f]Best case: 50% internal heat recovery in the stripping system. Worst case: no heat recovery
[g]Equal to 17·5 t/d of sulfuric acid at a density of 1800 kg/m^3
[h]Recovered as a 28% ammonium sulfate solution containing 6% nitrogen in the NRM-Strip/NRM-Scrub units. % nitrogen recovery was calculated from soluble nitrogen that enters the stripper
Bold values impact costs, while italicised 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; MWh_{th}, MegaWatthours thermal energy; MWh_{el}, MegaWatthours electricity

The estimated operational costs for air pumping were also directly calculated from the derived optimised air requirements (see results in Table 4). Electricity consumption related to the digester was estimated at ~24·5 MWh_{el}/d or 33 MJ/t manure, resulting in a cost of ~\$1850/d (Zwart *et al*., 2006) for a farm-scale digester of similar capacity as in the present study. Electricity use for the phase separation unit (gravity thickener) was estimated at ~100 kWh/d or 0·037 kWh/t, resulting in a cost of about \$7·5/d (USEPA, 1981; Zwart *et al*., 2006). For the struvite precipitation unit, electricity use amounts to ~250 kWh/d or 0·094 kWh m^3, which results in another \$19/d (Seymour, 2009).

Maintenance, material and labour costs for the precipitation unit and the stripping/scrubbing unit were obtained from the technology providers who delivered a budget proposal for this case. For the anaerobic digester and phase separation unit, these data were obtained by running simulations with the Capdet software (Symantec, 2014; USEPA, 1981), with user-defined input of the design data, operational conditions and waste stream characteristics. Maintenance costs for the CHP unit were also included, calculated at \$0·3/kWh produced at an operational basis of 8000 h/year (ECN, 2014).

Revenues from biogas production and fertiliser marketing were assumed. The methane produced was valorised using a CHP system with a conversion efficiency of 40% as thermal energy and 38% as electricity and with 22% heat losses (Verstraete and Vlaeminck, 2011). It was supposed that a market exists for the produced ammonium sulfate fertiliser and magnesium (Mg)–phosphorus fertiliser and that the products can be valued according to the current marketing value for nitrogen and phosphorus (Table 3). No incomes were currently considered for sulfur, but in the future, this macronutrient may also be of value, depending on the sulfur need of the agricultural crop. In the best-case scenario, also a market for the produced organic fertiliser was assumed according to its nutrient content, in contrast to the worst-case scenario.

Furthermore, when digesting animal manure, a significant reduction in carbon dioxide emissions can be expected. For pig manure, Zwart *et al*. (2006) quantified that 0·1 net tonne carbon dioxide equivalent (tCO_2e) can be saved per cubic metres of manure when treated by anaerobic digestion as compared to land spreading. In the economic analysis, it was assumed that an income of \$15/saved tCO_2e can be obtained from carbon dioxide emission reduction credits for anaerobic digestion under the Clean

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Development Mechanism defined in the Kyoto Protocol (Ciborowski, 2001; IPCC, 2007; The Clark Group LLC, 2012). Note that this assumption is based on current conservative US carbon dioxide prices ('carbon prices'). World carbon prices today are roughly \$40/tCO_2e (The Clark Group LLC, 2012). Other potential subsidies and fees, for example, gate fees for accepting animal manure in high-nutrient regions (Vaneeckhaute *et al.*, 2013), were not included in the analysis.

Finally, 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 (Charles *et al.*, 2014)

$$\text{NPV}(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} - \text{NINV} \quad (1)$$

in which R_t represents the net cash flow – that is, cash inflow − cash outflow, at time t; N is the total number of periods (years); t is the time of the cash flow; i is the discount rate – that is, the rate of return that could be earned on an investment in the financial markets with similar risk; and NINV is the net investment.

Results and discussion

The aim of the optimisation experiment was to use the NRM library for optimisation of the operational settings of the various unit processes in the proposed nutrient and energy recovery treatment train (Figure 1). Hence, as mentioned earlier, the reactor dimensions were fixed to the design values for each unit in the treatment train obtained from the various technology providers (Table 1), whereas the operational envelope including, for example, flow rates (Table 2), was optimised in order to reduce the net operational costs and to identify the true capacity of the system. The optimised scenario obtained is discussed in the next section. The resulting detailed economic analysis is presented in the section headed 'Detailed economic analysis'.

Optimised factors and performance indicators

The optimised values of the operational factors considered in the optimisation experiment are compiled in Table 4. Key performance indicators that were calculated from the optimised factors are also provided.

A first important remark is that the obtained optimal digester hydraulic retention time (HRT) (15 d) is low, definitely for an operational digester temperature of 28°C (lower end of the mesophilic range). It could even be questioned if such a scenario is realistic. A literature survey provided evidence that anaerobic digestion of swine manure at 20°C for 15–20 d can be considered promising for reducing indigenous performance indicators and pathogenic microorganism populations while providing sufficient waste stabilisation at relatively low costs (Côté *et al.*, 2006; Kearny *et al.*, 1993; Masse *et al.*, 2004; Nasir *et al.*, 2012). Wilkie (2000) evaluated 15 d as the lowest acceptable limit for pig manure monodigestion in a continuous stirred-tank reactor (CSTR) to guarantee a stable process, particularly at low temperature. However, optimal ranges 5–20 d have also been reported for various operational temperatures (USDA, 2007). Manure has a relatively low biodegradability and high acidification and ammonia inhibition potential compared to other organic waste sources (Jhong-Hwa *et al.*, 2006; Ossiansson and Lidholm, 2008). Hence, in order to improve the feasibility of manure digestion, operation at low temperature and high rate is of increasing interest, particularly in cold regions (Jhong-Hwa *et al.*, 2006; Ossiansson and Lidholm, 2008). Therefore, the obtained lowest-cost scenario was considered acceptable, although to date rather uncommon. Clearly, modelling of co-digestion of various waste streams is of interest and will be an aspect of future research.

Although the optimal digester HRT was low, the optimal loading rate to the digester was about 2·2 kg VSS/(m^3 d) (~65% VSS on TS content), which is an average value for an anaerobic CSTR (Tchobanoglous *et al.*, 2003). The value obtained for energy recovery (≈ 52 kWh/m^3 manure ≈ 5·8 m^3 methane/m^3 or 7·4 m^3 methane/m^3 without energy losses) is at the lower end of the experimental range obtained by Cesur and Albertson (2005) from which the input data was used – that is, 5·6–10 m^3 methane/m^3. This can be explained by the lower residence time (15 d against 33–45 d) and reactor temperature (28°C against 35°C) in the simulated system. As such, ~55% COD and ~45% VSS removal was obtained in the simulated system, while at full scale an actual average removal of 71% COD and 65% VSS was observed. The obtained % COD and VSS destruction are in line with the experimental findings of Elbeshbishy *et al.* (2010) for mesophilic anaerobic digestion of hog manure at an HRT of 15 d – that is, 55–60% and 45–50%, respectively. Also, the obtained methane production is in good agreement with full-scale values for large-scale mesophilic monodigestion of pig manure obtained by Lithania (2006) – that is, 7·6 m^3 methane/m^3 at an HRT of 15 d – and by Kasper and Peters (2012) – that is, 5·2–13 m^3 methane/m^3 pig manure. Due to the high acidification and ammonia inhibition potential during monodigestion of pig manure, a higher liquid flow rate was in this case more beneficial than the addition of a high calcium (Ca) dose (optimum = no external calcium addition).

Another possible reason for both the rather low HRT and temperature is related to the interactions of the digester's operating conditions with the economics of nutrient recovery downstream in the treatment train. As such, total revenues from mineral fertiliser production were in this case higher than the revenues obtained through biogas production. On top of that, the digested separated solids obtained may be reused as an organic fertiliser containing nitrogen, phosphorus and potassium (from bacterial cells), as well as calcium and magnesium. Depending on local regulations, important revenues can be obtained from organic fertiliser marketing. However, in nutrient-rich regions, a cost is often attached to the disposal of this product. Depending on the situation, additional costs and energy requirements may also be attributed to solids drying and/or pasteurisation.

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Furthermore, an interesting observation is that, under the optimal conditions an important amount of calcium (~64% of the daily digester input) was removed as calcium carbonate ($CaCO_3$) precipitate with the separated solids. Hence, based on the simulations, liquid–solid separation of digestate prior to struvite precipitation and ammonia stripping seems to provide an interesting option to reduce calcium inhibition in the downstream processes. Indeed, no calcium precipitation was detected in the stripping column or in the precipitation unit. However, the fraction of non-settleable precipitates (f_ns_P) on solid–liquid separation is an important factor, for which an optimal value of 25% was found. In practise, this value may be hard to reach without the addition of coagulants, such as lime (calcium hydroxide ($Ca(OH)_2$) or calcium oxide (CaO)). Excess lime may also cause calcium/phosphorus precipitation at pH values higher than 10. Depending on local fertiliser markets, the latter may be interesting or not. Further research is required to experimentally determine the f_ns_P in the phase separation unit under different operating conditions and input waste stream compositions.

Also of interest is that using magnesium hydroxide ($Mg(OH)_2$) as the sole chemical product for both phosphorus precipitation and nitrogen stripping (+ carbon dioxide stripping) resulted in high recovery efficiencies for both nitrogen and phosphorus at low costs. This is related to the reduced inhibition of chlorides (by avoiding magnesium chloride hexahydrate ($MgCl_2{\cdot}6H_2O$) dosing) on nitrogen stripping and of sodium (by avoiding sodium hydroxide (NaOH) dosing) on phosphorus precipitation (Vaneeckhaute *et al*., 2018b). The obtained electricity need for air pumping is relatively low, since it was assumed that air is continuously recycled between the stripper and scrubber units (RVTPE, 2014). The electricity need can be entirely covered by the recovered electricity in the CHP system. Note that the heat needed for stripping was higher than for digestion. However, internal heat recovery in the strip–scrub system can be achieved (recovery from the stripped flow), resulting in total energy savings of more than 50%, as indicated by technology providers. The heat recovery potential in the strip–scrub system will determine whether all heat requirements can be covered by the heat produced by the CHP system or whether external heat has to be supplied.

No effluent quality criteria were set for the present case since the focus was on nutrient and energy recovery. The final effluent resulting from the stripping unit contains very low soluble phosphorus concentrations (< detection limits of analytical instruments i.e. 0·05 mg/l for a continuous-flow analyser) and relatively low nitrogen concentrations – that is, ~350 mg/l. This nitrogen content is generally too high for effluent discharge. However, the water may be recycled as process water in the plant – for example, for cleaning of the phase separation unit. If specific effluent quality criteria for nitrogen need to be achieved, the treatment train may be further optimised to reach these specifications. A low-cost final effluent treatment may also be considered or the water may be recycled to a nearby waste water treatment plant. In any case, effluent quality criteria will impact the cost of the treatment train.

Detailed economic analysis

An overview of the annual treatment train operational costs and revenues, as well as the capital costs for each unit process in the treatment train, is presented in Table 5. The estimation is based on an operational basis of 8000 h/year, which is a common figure (ECN, 2014; Vaneeckhaute, 2009). For convenience of discussion, all costs are expressed in US dollars.

First, it should be remarked that fixed and variable costs are highly influenced by the specifications of the applied technology (i.e. the design, the material used for construction, isolation etc.), the options for recovered product valorisation (e.g. biogas conversion into electricity, heat, fuel or others) and the location (climate, market prices, land costs, regulations etc.). Hence, it should be emphasised that various assumptions (see later) had to be made to obtain the values represented in Table 5. The aim of the economic analysis was merely to provide an order of magnitude of the economic feasibility of installing a nutrient recovery treatment train, rather than providing exact values.

As depreciation costs and loan service costs vary depending on when and where money is borrowed, stakeholders may be interested in the yearly net cash flows determined by the variable costs and revenues. On the basis of the optimised 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 year) (\$55–130/(t TS year)) 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 zero-cost biorefinery for nutrient and energy recovery from manure could be achieved. As one could be critical on the optimised digester temperature and residence time used in this study (see the section headed ‘Optimised factors and performance indicators’), the economic analysis was also performed for a digester operated at a temperature of 50°C with an HRT of 15 d and a calcium hydroxide dose of 21 t/d. The financial benefits in this scenario amounted to \$2–6/(m^3 manure year), which is competitive with the aforementioned optimal scenario. Hence, if a high-temperature treatment is required for product pasteurisation, the latter scenario may be targeted, although it is less sustainable in terms of consumables (heat and chemical use). At an HRT of 30 d, the financial benefits amounted to about \$3/(m^3 year) in the best case, but a loss of \$1·5/(m^3 year) 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 optimisation of heat balances in the configuration of future integrated nutrient and energy recovery facilities.

Assuming an average discount rate of 6% (Harrison, 2010) and a depreciation period of 20 years for all unit processes (Symantec,

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Table 5. Costs and revenues for the optimised nutrient and energy recovery treatment train

Unit	Costs: $ thousands/year								
	Fixed costs	Variable costs					Revenue resource recovery		
		Opex				Maintenance, material and labour[c]	Biogas + fertiliser		Carbon dioxide credits[f]
	Capex	Heat (best)[a]	Heat (worst)[b]	Electricity	Chemicals		Best[d]	Worst[e]	
AD + CHP[g]	22 500	694	1198	621	—	977	3547	3547	1334
Phase separation[h]	1250	—	—	2·5	To be evaluated	226	1741	0	—
Precipitation[i]	4750	—	—	6·3	102	48	1468	1468	—
Strip/scrub[j]	680	1034	2069	74	913	6·8	2365	2365	—
Others[k]	2000	—	—	—	—	—	—	—	—
Rounded total	31 000	1750	3250	700	1000	1250	9100	7400	1350

[a]Best case: 10% heat losses (Wu and Bibeau, 2010; Zupancic and Ros, 2003). Waste input temperature: 20°C (Symantec, 2014; USEPA, 1981)
[b]Worst case: heat requirement that is 1·9 times higher than the theoretical heat required for manure heating (LAWPCA, 2009; Tchobanoglous *et al.*, 2003; USEPA, 1981; Vaneeckhaute, 2009)
[c]Operator labour rate: $51·5/h (Symantec, 2014; USEPA, 1981). Maintenance labour rate: $43·5/h (Symantec, 2014; USEPA, 1981)
[d]Best case: 50% internal heat recovery in the stripping system
[e]Worst case: no heat recovery
[f]Net carbon dioxide equivalent emission savings through manure digestion compared to manure spreading: 0·1 t/m^3 manure (Zwart *et al.*, 2006). Revenues from carbon dioxide emission reduction credits: $15/tCO$_2$e (IPCC, 2007; The Clark Group LLC, 2012)
[g]Unit process construction + equipment costs: eight digester tanks of 5000 m^3 with floating cover, gas circulation unit, heating unit, gas safety and cleaning equipment, sludge pump and conventional heat and power system (ECN, 2014; Symantec, 2014; USEPA, 1981)
[h]Unit process construction + equipment costs: standard gravity thickener (Symantec, 2014; USEPA, 1981)
[i]Unit process construction + equipment costs: precipitation/crystallisation unit and sludge pump (Technology Providers, personal communication, 2014)
[j]Unit process construction + equipment costs: feed pump, stripper column, stripper discharge pump, ventilator, absorption column, circulation pump, sulfuric acid dosing pump, feed heat exchanger, secondary heat exchanger, piping and fittings (Technology Providers, 2014)
[k]Other construction costs, such as land costs (agricultural land is assumed), legal costs, inspection costs, costs of laboratory and administration buildings and miscellaneous costs (Symantec, 2014; USEPA, 1981)
AD, anaerobic digester; Capex, capital expenditures; CHP, conventional heat and power; Opex, operational expenditures

2014; USEPA, 1981), except for the stripping unit, for which a depreciation period of 8 years was assumed as advised by technology providers, the nutrient recovery project presented would have a positive NPV in year 7 of the 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 USA – that is, 6·9–8·9 years based on a survey of 24 plants (Vik, 2003). The NPV after 20 years amounted to about $3·5 million, resulting in average net financial benefits of ~$2/(m^3 manure year) ($40/(t TS year)) over 20 years.

The internal rate of return (IRR) – that is, 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 biorefinery for nutrient and energy recovery in the Netherlands – that is, 19–21% (Gebrezgabher *et al.*, 2010). In the worst-case scenario, the IRR after 20 years was only 5%. Generally, the project should be accepted only if the IRR is higher than the firm's cost of capital. Hence, based on the analysis (worst case against 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 fertilisers and the subsidies obtained. For instance, when accounting for an income of $40/net saved tCO2e (current global market price of carbon (The Clark Group LLC, 2012)) instead of the conservative US carbon prices, the IRR would be around 26 and 14% in the best and worst cases, respectively, resulting in a revenue of $1·3–3·4/(m^3 manure year) ($25–70/(t TS year)) averaged over 20 years.

It should be emphasised that pig manure has been used as a case study in this paper. The obtained results may hence be different when using different input streams. It is expected that co-digestion of various waste streams – for example, pig manure with food waste – can further improve the overall cost balance. Moreover, the reactor dimensions have been fixed to treat a flow rate of 2000 m^3/d. Different flow rates will obviously result in different reactor dimensions, which may also impact the optimal process conditions. Hence, more optimisation case studies using the NRM library are required to draw conclusions on the economic viability of biorefineries for energy (biogas) and nutrient recovery from alternative waste streams and for different flow rates.

Finally, it should be remarked that the benefits of nutrient and energy recovery over the whole value chain may be much higher than presented, taking into account, for instance, the saved nutrient emissions to air and waterbodies by avoiding spreading and storing of untreated animal manure, and the saved energy and costs by

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reducing synthetic mineral fertiliser production. For example, the production of mineral nitrogen through the Haber–Bosch process consumes 35·2–40·5 GJ/t ammonium (NH_4), which is equal to about \$750–850/t ammonium (Efma, 2014; Foged, 2011; Vaneeckhaute *et al*., 2013). Moreover, Zwart *et al*. (2006) estimated that anaerobic digestion of animal manure could result in an overall nutrient emission (e.g. greenhouse gases and leaching) reduction of 95% compared to manure spreading. Holistic life cycle analyses are needed to evaluate the overall environmental impact of anaerobic digestion and nutrient recovery treatment trains for biobased fertiliser production, as presented earlier. Such studies are being conducted in collaboration with the Luxembourg Institute of Science and Technology (Esch-sur-Alzette, Luxembourg) (Vázquez-Rowe *et al*., 2015), Bangor University (Gwynedd, UK) (Styles *et al*., 2016; Vaneeckhaute *et al*., 2018c) and the University of Bath (Bath, UK) (Vaneeckhaute *et al*., 2018c). Moreover, future work will focus on the coupling of the NRM treatment train to soil nutrient balance models, agroeconomic tools and spatiotemporal decision-support tools in order to optimise nutrient recovery strategies throughout the whole waste–nutrient–soil–plant system. The obtained information could then be used for further policymaking in terms of subsidies, thereby stimulating the full-scale implementation of nutrient recovery projects.

Conclusions and perspectives

The potential of the NRM library for optimisation 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 zero-cost biorefinery for nutrient and energy recovery could be constructed. Under the optimised conditions and assumptions made, financial benefits could even be achieved. The NPV after 20 years amounted to about \$3·5 million, resulting in average net financial benefits of ~\$2/(m^3 manure year) or \$40/(t TS year) over 20 years. The IRR after 20 years was 18% in the best case. Results indicate clear interactions between the various unit processes in the treatment train, thereby confirming the need for global optimisation of complete integrated nutrient and energy recovery treatment trains, as presented in this paper. Moreover, results indicate that subsidies, fertiliser marketing potential and heat balances are key factors determining the feasibility of resource recovery projects. Hence, process and design engineers should focus on the optimisation of heat balances in the configuration of future integrated nutrient and energy recovery facilities. Fertiliser regulations and subsidies should be adjusted accordingly.

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REFERENCES

Batstone DJ, Amerlinck Y, Ekama G *et al.* (2012) Towards a generalized physicochemical framework. *Water Science and Technology* **66(6)**: 1147–1161.

BENC (Bio-Economy Network Canada) (2015) *Towards an Integrated Action Plan for the Bio-economy*. Natural Resources Canada, Ottawa, ON, Canada.

Brouckaert CJ, Ikumi DS and Ekama GA (2010) A three phase anaerobic digestion model. *Proceedings of the 12th IWA Anaerobic Digestion Conference (AD12), Guadalajara, Mexico.*

Cesur D and Albertson ML (2005) Modification of anaerobic digestion model no. 1 for accumulation and biomass recycling. *Proceedings of the AGU Hydrology Days 2005, Fort Collins, CO, USA.*

Charles RM, McGuigan J and Rao R (2014) *Contemporary Financial Management*. Cengage Learning, Stamford, CT, USA.

Charlton SR and Parkhurst DL (2011) Modules based on the geochemical model PHREEQC for use in scripting and programming languages. *Computers and Geosciences* **37(10)**: 1653–1663.

Ciborowski P (2001) *Anaerobic Digestion of Livestock Manure for Pollution Control and Energy Production: a Feasibility Assessment*. Minnesota Pollution Control Agency, Saint Paul, MN, USA.

Côté C, Massé DI and Quessy S (2006) Reduction of indicator and pathogenic microorganisms by psychrophilic anaerobic digestion in swine slurries. *Bioresource Technology* **97(4)**: 686–691, https://doi.org/10.1016/j.biortech.2005.03.024.

ECN (Energy Research Centre of the Netherlands) (2014) *Combined Heat and Power (CHP): Large-scale*. ECN, Petten, the Netherlands.

Efma (European Fertilizer Manufacturers Association) (2014) *Annual Overview 2014*. Efma, Brussels, Belgium.

Elbeshbishy E, Nakevski A, Hafez H, Ray M and Nakhla G (2010) Simulation of the impact of SRT on anaerobic digestion of ultrasonicated hog manure. *Energies* **3(5)**: 974–988, https://doi.org/10.3390/en3050974.

EuropaBio (2015) *Building a Bio-based Economy for Europe in 2020*. EuropaBio, Brussels, Belgium.

FAO (Food and Agricultural Organization of the UN) (2004) Mixed farming systems in the developed world: nutrient surpluses. In *Livestock Production, the Environment and Mixed Farming Systems* (Blackburn H (ed.)). FAO, ID, USA.

Flores-Alsina X, Mbamba CK, Solon K *et al.* (2015) A plant-wide aqueous phase chemistry module describing variations and ion speciation/pairing in wastewater treatment process models. *Water Research* **85**: 255–265, https://doi.org/10.1016/j.watres.2015.07.014.

Foged HL (2011) Renewable energy (manure-based anaerobic digestion). *Proceedings of the TAIEX Workshop on Best Practices in Manure Management in Livestock Production on Farms, Zagreb, Croatia.*

Gablonsky JM and Kelley CT (2001) A locally-biased form of the DIRECT algorithm. *Journal of Global Optimization* **21(1)**: 27–37, https://doi.org/10.1023/A%3A1017930332101.

Gebrezgabher SA, Meuwissen MPM, Prins BAM and Oude Lansink AGJM (2010) Economic analysis of anaerobic digestion – a case of Green power biogas plant in The Netherlands. *NJAS – Wageningen Journal of Life Sciences* **57(2)**: 109–115, https://doi.org/10.1016/j.njas.2009.07.006.

Harrison M (2010) *Valuing the Future: the Social Discount Rate in Cost–Benefit Analysis*. Productivity Commission, Canberra, Australia.

Icis (2014) *Indicative Chemical Prices A–Z*. Icis, Surrey, UK. See http://www.icis.com/chemicals/channel-info-chemicals a-z/ (accessed 05/09/2014).

IPCC (2007) *Climate Change 2007: Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

Jhong-Hwa A, Trong HD, Sang DK and Seokhwan H (2006) The effect of calcium on the anaerobic digestion treating swine wastewater. *Biochemical Engineering Journal* **30(1)**: 33–38, https://doi.org/10.1016/j.bej.2006.01.014.

Johnson SG (2008) *The NLopt Nonlinear-optimization Package*. Massachusetts Institute of Technology, Cambridge, UK. See http://ab-initio.mit.edu/nlopt (accessed 03/09/2014).

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Jones DR, Perttunen BE and Stuckman S (1993) Lipschitzian optimization without the Lipschitz constant. *Journal of Optimization Theory and Applications* **79(1)**: 157–181.

Kasper GJ and Peters B (2012) *Monodigestion of Pig Manure at Farm Scale*. Wageningen University and Research, Wageningen, the Netherlands, Report 632.

Kearny ET, Larkin MJ, Frost JP and Levett PN (1993) Survival of pathogenic bacteria during mesophilic anaerobic digestion of animal waste. *Journal of Applied Bacteriology* **75(3)**: 215–219, https://doi.org/10.1111/j.1365-2672.1993.tb02768.x.

Khiewwijit R, Temmink H, Rijnaarts H and Keesman KJ (2015) Energy and nutrient recovery for municipal wastewater treatment: how to design a feasible plant layout? *Environmental Modelling and Software* **68**: 156–165, https://doi.org/10.1016/j.envsoft.2015.02.011.

LAWPCA (Lewiston Auburn Water Pollution Control Authority) (2009) *Anaerobic Digestion and Energy Recovery*. LAWPCA, Augusta, ME, USA.

Lithania K (2006) *Roaki Pig Farm Demonstration Biogas Plant*. Folkecenter for Renewable Energy and Environmental Protection Ministry, Hurup Thy, Denmark.

Masse DI, Croteau F, Masse L and Danesh S (2004) The effect of scale-up on the digestion of swine manure slurry in psychrophilic anaerobic sequencing batch reactors. *Bioresource Technology* **75(3)**: 205–211, https://doi.org/10.13031/2013.16541.

Nasir IM, Ghazi TIM and Omar R (2012) Anaerobic digestion technology in livestock manure treatment for biogas production: a review. *Engineering in Life Sciences* **258(3)**: 258–269, https://doi.org/10.1002/elsc.201100150.

Ossiansson E and Lidholm O (2008) *Application, Uncertainty and Sensitivity Analysis of the Anaerobic Digestion Model by Siegrist et al. 2002 on Household Waste Digestion*. MSc thesis, Lund University, Lund, Sweden.

RVTPE (RVT Process Equipment) (2014) *Ammonia Recovery from Liquids and Removal of Gases*. RVTPE, Steinwiesen, Germany.

Seymour D (2009) Can nutrient recovery be a financially sustainable development objective? *Proceedings of the Annual Conference of the Pacific North West Clean Water Association, Boise, ID, USA.*

Styles D, Borjersson P, D'Hertefeldt T *et al.* (2016) Climate regulation, energy provisioning and water purification: quantifying ecosystem service delivery of bioenergy willow grown on riparian buffer zones using life cycle assessments. *AMBIO – a Journal of the Human Environment* **45(8)**: 872–884, https://doi.org/10.1007/s13280-016-0790-9.

Symantec (2014) *Computer Assisted Procedure for the Design and Evaluation of Wastewater Treatment Systems (CAPDET)*. Symantec, Mountain View, CA, USA.

Tchobanoglous G, Burton F and Stensel HD (2003) *Metcalf & Eddy Wastewater Engineering: Treatment and Reuse*. McGraw-Hill, New York, NY, USA.

The Clark Group LLC (2012) *An Overview of Methane Digesters: Costs, Benefits and the Potential for Revenue in a Carbon Economy*. The Clark Group LLC, Washington, DC, USA.

UNEP (UN Environment Programme) (2013) *Green Economy and Trade: Trends, Challenges and Opportunities*. UNEP, Nairobi, Kenya.

USDA (US Department of Agriculture) (2007) *An Analysis of Energy Production Costs from Anaerobic Digestion Systems on U.S. Livestock Production Facilities*. Natural Resources Conservation Service, USDA, Washington, DC, USA.

USEPA (US Environmental Protection Agency) (1981) *Computer Assisted Procedure for the Design and Evaluation of Wastewater Treatment Systems (CAPDET): Program User's Guide*. USEPA, Washington, DC, USA.

USEPA (2013) *US Dairy Industry's Report National Market Value of Anaerobic Digester Products*. Innovation Center for US Dairy, Rosemont, IL, USA.

Vaneeckhaute C (2009) *Energy Recovery from Biogas and Post-treatment of Digestate into Qualitative End-products*. Goemaere Eneco Energie, Ghent University, Ghent, Belgium.

Vaneeckhaute C, Meers E, Michels E, Buysse J and Tack FMG (2013) Ecological and economic benefits of the application of biobased mineral fertilizers in modern agriculture. *Biomass and Bioenergy* **49**: 239–248, https://doi.org/10.1016/j.biombioe.2012.12.036.

Vaneeckhaute C, Lebuf V, Michels E *et al.* (2017) Nutrient recovery from bio-digestion waste: systematic technology review and product classification. *Waste and Biomass Valorization* **8(1)**: 21–40, https://doi.org/10.1007/s12649-016-9642-x.

Vaneeckhaute C, Claeys FHA, Tack F *et al.* (2018a) Development, implementation, and validation of a generic nutrient recovery model (NRM) library. *Environmental Modelling and Software* **99**: 170–209, https://doi.org/10.1016/j.envsoft.2017.09.002.

Vaneeckhaute C, Remigi E, Tack FMG *et al.* (2018b) Optimizing the configuration of integrated nutrient and energy recovery treatment trains: a new application of global sensitivity analyses to the generic nutrient recovery model (NRM) library. *Bioresource Technology* **269**: 375–383, https://doi.org/10.1016/j.biortech.2018.08.108.

Vaneeckhaute C, Styles D, Prade T *et al.* (2018c) Closing nutrient loops through decentralized anaerobic digestion of organic residues in agricultural regions: a multi-dimensional sustainability assessment. *Resources, Conservation and Recycling* **136**: 110–117, https://doi.org/10.1016/j.resconrec.2018.03.027.

Vanhooren H, Meirlaen J, Amerlinck Y *et al.* (2003) Modelling biological wastewater treatment. *Journal of Hydroinformatics* **5**: 27–50.

Vázquez-Rowe I, Golkowska K, Lebuf V *et al.* (2015) Environmental assessment of digestate treatment technologies using LCA methodology. *Waste Management* **43**: 442–459, https://doi.org/10.1016/j.wasman.2015.05.007.

Verstraete W and Vlaeminck SE (2011) ZeroWasteWater: short-cycling of wastewater resources for sustainable cities of the future. *Journal of Sustainable Development* **18(3)**: 253–264, https://doi.org/10.1080/13504509.2011.570804.

Vik TE (2003) *Anaerobic Digester Methane to Energy: a Statewide Assessment*. Dee McMahon Associates, Inc., Neenah, WI, USA.

Wilkie AC (2000) Anaerobic digestion: holistic bioprocessing of animal manures. *Proceedings of the Animal Residuals Management Conference, Alexandria, VA, USA*, pp. 1–12.

Wu B and Bibeau EL (2010) Development of 3-D anaerobic digester heat transfer model for cold weather applications. *Transactions of the ASABE* **49(3)**: 749–750, https://doi.org/10.13031/2013.20482.

Ye ZL, Chen SH, Wang SM *et al.* (2010) Phosphorus recovery from synthetic swine wastewater by chemical precipitation using response surface methodology. *Journal of Hazardous Materials* **176(1–3)**: 1083–1088, https://doi.org/10.1016/j.jhazmat.2009.10.129.

Zupancic GD and Ros M (2003) Heat and energy requirements in thermophilic anaerobic sludge digestion. *Renewable Energies* **28(14)**: 2255–2267, https://doi.org/10.1016/S0960-1481(03)00134-4.

Zwart KB, Oudendag DA, Ehlert PAI and Kuikman PJ (2006) *Sustainability Codigestion of Animal Manure*. Wageningen University and Research, Wageningen, the Netherlands, Alterra-Report 1439.

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