Environmental assessment of an innovative scheme for the co-management of wastewater and domestic organic waste in small communities

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Abstract

This study aims at the identification of the environmental impacts of the combined treatment of wastewater and domestic organic waste (DOW) for a small and decentralised community. The treatment scheme includes anaerobic digestion of wastewater, fermentation of DOW to produce the carbon source required for the nutrients removal in a sequencing batch reactor (SBR) and the composting of the sludge generated along the process. Alternative scenarios were proposed and evaluated in order to identify potential environmental improvements. The SBR process, the fermentation tank and the composting unit were identified as the main *hotspots* from an environmental point of view. This was mainly due to derived direct emissions as well as the production of electricity and diesel required in these processes.

Partial recirculation of the fermented liquid to the anaerobic reactor had a positive effect due to the increase biogas yield that entails higher environmental credits due to avoided heat production from natural gas. The partial nitritation-anoxic ammonium oxidation (anammox) (PN-ANM) was identified as the most energy efficient nitrogen removal option. However, the process does not remove phosphorus; exhibiting the worst performance in terms of eutrophication related categories.

Keywords

Anaerobic digestion, decentralised treatment system; environmental profile; environmental hotspots

1. Introduction

Wastewater management is capital intensive for investment as well as operation and maintenance costs (up to three times more expensive than the costs of drinking water supply). The selection of the most suitable approach for wastewater management should be in accordance with the specific characteristics of the specific area (Massoud et al., 2009). The centralised strategy is not feasible in many places, or not the most cost-effective alternative in some cases. Thus, in communities with low population densities and dispersed households decentralised systems for wastewater treatment can be a long-term solution and a more reliable and cost-effective option (Massoud et al., 2009).

Domestic organic waste (DOW) is generated in households. According to the European Commission, around 90 million tonnes of food waste are generated in the EU each year (European Commission, 2010). The Landfill Directive (EU, 1999) requires from Member States to gradually divert organic wastes away from landfills, towards material and energy recovery. The way to achieve a 'low-carbon footprint' society is by converting waste treatment technologies into resource recovery ones (Nakakubo *et al*., 2012). The application of combined schemes for the co-management of both wastewater and DOW could offer several environmental advantages especially for small communities. Anaerobic treatment of wastewater should be a core technology that can be employed in decentralized sanitation systems (Katsou et al., 2014). There are several advantages linked to anaerobic digestion such as the recovery of carbon in the form of methane suitable for energy production (Van Lier et al., 2002), while the investment costs are lower compared with aerobic systems (Van Lier et al., 2002). The direct discharge of the anaerobic supernatant is not a viable option since has high ammonium and phosphate content (Frison et al., 2013). The biological processes are more cost effective than the physicochemical ones and have the advantage that nitrogen is converted into a gaseous form. Due to the ratio between biodegradable organic matter and total nitrogen, the addition of external carbon source is needed in order to accomplish effective denitrification. The acidogenic fermentation of DOW could provide the short-chain fatty acids (SCFAs) required to promote the biological removal of nutrients.

The main objective of this study was to assess a system designed for the decentralised co-management of wastewater and DOW in a small community of 2,000 population equivalent (PE) from an environmental point of view. Alternative scenarios were examined and evaluated in order to identify potential environmental improvements. The methodology selected in order to perform the environmental assessment was the life cycle assessment (LCA).

2. Materials and methods

2.1. Goal and scope definition

As mentioned, a system for the co-management of wastewater and DOW in a small community of 2,000 PE have been designed and evaluated from an environmental perspective. The evaluation of the environmental performance of the innovative treatment system was based on the development and comparison of alternative scenarios considering technical and environmental criteria.

The baseline system consisted of anaerobic treatment of wastewater in an upflow anaerobic sludge blanket (UASB), the fermentation of DOW to produce the carbon source rich in SCFAs required for nutrient removal in a sequencing batch reactor (SBR) through conventional nitrification denitrification and a composting unit for the treatment of the fermented solid and the dewatered waste activated sludge produced from the biological process to be further applied to agricultural land.

The alternative scenarios include different options for the biological removal of nitrogen in the SBR such as conventional nitrification denitrification, short-cut nitrification-denitrification (SCND) and partial nitritation-anammox (PN-ANM). Furthermore, the partial recirculation of the fermented liquid to the UASB was investigated resulting in increased biogas yield.

2.2. Methodology

Wastewater treatment processes are end-of-pipe technologies designed to deal with pollutants present in wastewaters (Rodriguez-Garcia et al., 2014). An exhaustive analysis is required to avoid exporting environmental problems over time or space. LCA is a methodological framework useful to determine the environmental impacts of a system, product or activity (ISO 14040, 2006).

The standard approach for functional unit (FU) is typically based on the volume of treated wastewater, the environmental load per PE or the reduction of the eutrophication potential (Rodriguez-Garcia et al., 2011). The selected FU in this study was the service provided by the system, which is the management of the wastewater and DOW produced by a population of 2,000 PE per day.

The Life Cycle Inventory (LCI) for each scenario was developed including data coming from energy and mass balances regarding organic matter and nutrients (nitrogen and phosphorus). The mass balances were developed based on real data from operation of pilot plants located in Northern Italy (Katsou et al., 2014). Furthermore, the LCI was completed with transport and agricultural machinery, energy consumption, infrastructure requirements and emissions derived from each treatment process. Moreover, background data regarding the production of all required inputs such as the production of chemicals, infrastructure, machinery, electricity were taken from ecoinvent® database.

2.3. Description of the baseline system and alternative scenarios proposed

The baseline treatment system included the treatment of wastewater in a UASB, where biogas was produced and subsequently converted into heat. DOW was fermented to produce the carbon source, which was then fed to the SBR, where the denitrification via nitrate was performed. After the SBR process, the final effluent was considered to be discharged into river. The sludge produced along the system was sent for composting and the produced compost was applied to land as soil conditioner. Furthermore, it was assumed that both the production of heat from biogas and the use of compost within the examined system would replace the production of heat from natural gas and the use of peat as a soil conditioner (Saer et al., 2013). All processes included in the baseline scenario are outlined in **Figure 1**.

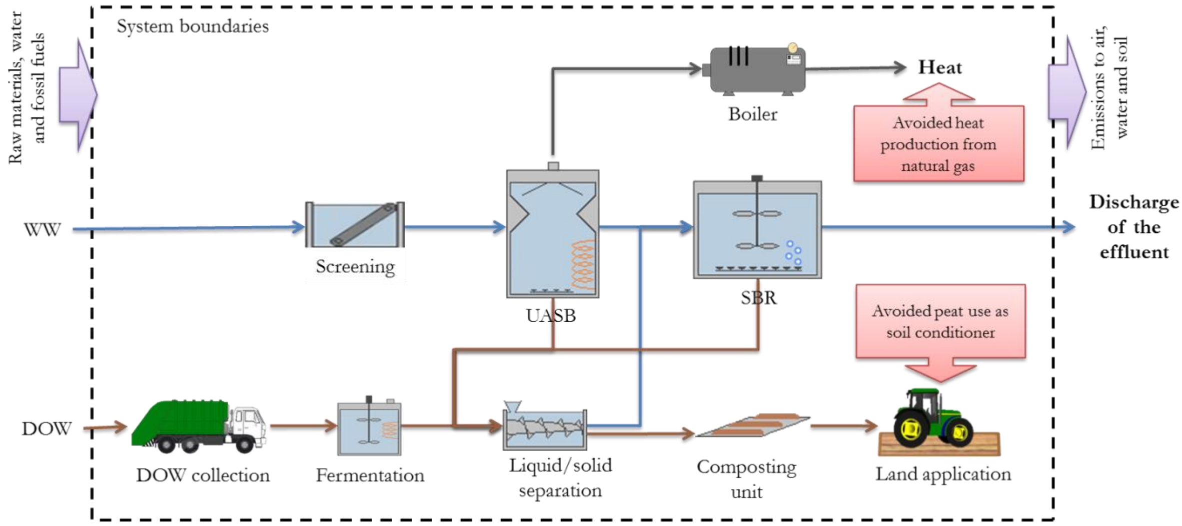

Figure 1. Flowchart of the baseline system

The main characteristics of wastewater and DOW considered in the baseline system as well as the composition of the final effluent are summarized in **Table 1**.

Table 1. Summary of the most important inventory data for the baseline scenario.

Parameters		
Wastewater flow	$m^3 \cdot d^{-1}$	400
Chemical oxygen demand (COD)	$g\ COD \cdot PE^{-1} \cdot d^{-1}$	120
N	$g\ N \cdot PE^{-1} \cdot d^{-1}$	12.0
P	$g\ P \cdot PE^{-1} \cdot d^{-1}$	1.8
DOW treatment	$kg \cdot d^{-1}$	500
Total solids (TS)	%	25
Chemical oxygen demand (COD)	$mg\ COD \cdot gTS^{-1}$	893
N	$mg\ N \cdot gTS^{-1}$	26
P	$mg\ P \cdot gTS^{-1}$	2.1
Methane production	$m^3 \cdot d^{-1}$	63
Heat production	$kWh \cdot d^{-1}$	601
Compost production	$kg \cdot d^{-1}$	523
C	% W/W	24
N	% W/W	1
P	% W/W	0.6
Effluent flow	$m^3 \cdot d^{-1}$	401
Total solids (TS)	$mg \cdot L^{-1}$	22
Chemical oxygen demand (COD)	$mg \cdot L^{-1}$	51
N	$mg \cdot L^{-1}$	9.7
P	$mg \cdot L^{-1}$	3.8

Additionally, the environmental consequences of different processes were assessed: short-cut nitrification-denitrification (SCND) (i.e. nitritation/denitritation) (Scenario 1b) and partial nitritation-anoxic ammonium oxidation (anammox) (PN-ANM) (Scenario 1c). The nitrogen removal processes were also evaluated considering that a fraction of the fermented liquid (35%) is recirculated to the anaerobic reactor (Scenarios 2a, 2b and 2c). All the examined scenarios are illustrated in **Figure 2**.

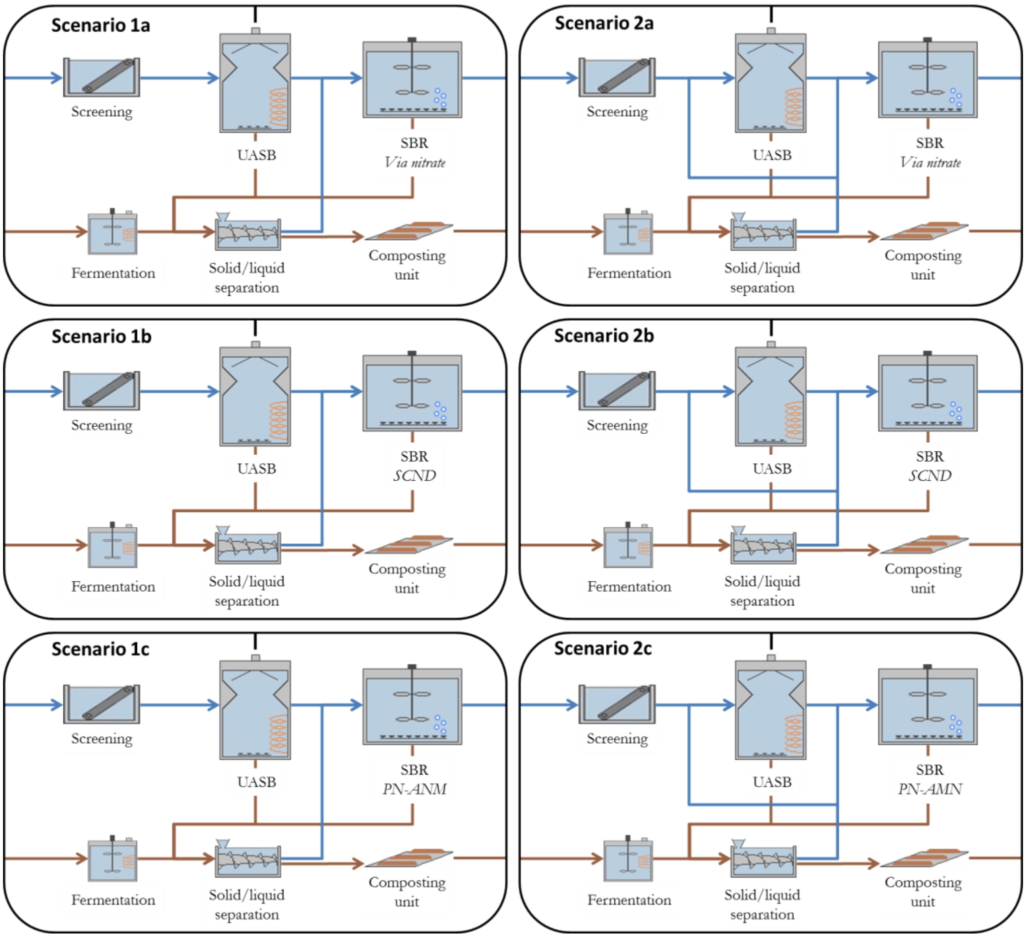

Figure 2. Alternative scenarios focusing on nitrogen removal with and without recirculation of the fermented liquid into the anaerobic treatment unit.

3. Results and discussion

3.1. Environmental performance of the treatment system proposed

The environmental profile was estimated using the characterisation factors provided by the ReCiPe Midpoint methodology (Goedkoop et al., 2009). The impact categories selected were climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME) and fossil depletion (FD).

Looking at the natural carbon cycle, biogenic carbon could be considered as climate-neutral, since the equivalent amount of carbon dioxide emitted from an organic source is previously absorbed during plant growth. However, the objective of this study is to compare different organic waste management scenarios that generate different levels of carbon dioxide emissions (Blengini, 2008).Thus, carbon dioxide from biogenic sources has been considered for the characterization of CC by assigning a characterization factor of 1 for CC.

In the results of **Table 2**, positive values are indicative of environmental burdens whereas negative values denote environmental credits or benefits accrued from the uptake of carbon dioxide, as well as from avoided processes. OD achieved positive environmental results due to the environmental credits provided by the avoided processes (avoided heat production from natural gas and avoided peat use).

Table 2. Environmental characterisation of the treatment system under study

Impact category	Unit	Baseline system
CC	kg CO2 eq	488
OD	kg CFC-11 eq	$-9.5\cdot10^{-7}$
TA	kg SO2 eq	2.7
FE	kg P eq	1.6
ME	kg N eq	5.0
POF	kg NMVOC	0.6
FD	kg oil eq	22

Owing to this treatment system, environmental impact in eutrophication related categories is lower compared with the impact produced when wastewater is discharged without any treatment. Specifically, in terms of FE were 2.25 times lower than those from the discharge of wastewater without treatment and 4.75 times lower in terms of ME.

3.2. Identification of the environmental hotspots within the treatment system

The relative contributions of the processes involved in the system under examination regarding each impact category selected are shown in **Figure 3**.

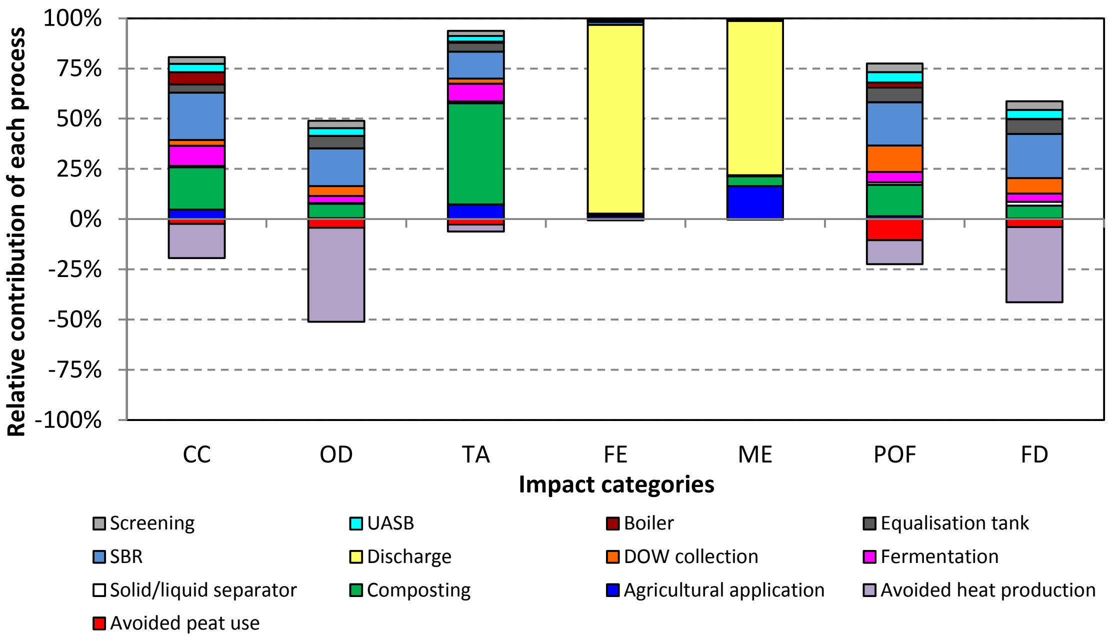

Figure 3. Distribution of the contribution of each process involved in the baseline scenario.

Concerning the impact categories of CC, OD and POF, the major environmental burdens were related to the SBR process (19-24%), the fermentation (4-10%) and the composting unit (7-21%). Environmental impacts related with these impact categories that occur in the SBR process were related mainly with the production of the electricity required during the aeration phase. Moreover, emissions of nitrous oxide and carbon dioxide generated from the SBR (biological process) have a direct influence on CC. Concerning the fermentation tank, the environmental impacts are related with the production of electricity consumed in heating and mixing operations in the reactor. Additionally, methane emissions contributed to the environmental impacts produced in terms of CC. Emissions from diesel consumption in the tractor operation for turning the compost piles were also identified as an important contributor to these impact categories. Moreover, direct emissions from the biological degradation of the sludge in the composting process, such as carbon dioxide, methane and nitrous also had an important contribution to CC. Ammonia emissions that are also generated during the composting process as well as in the fermentation tank were the main contributor in TA (50% and 9%, respectively). The discharge of the treated effluent into the river, due to phosphorus and nitrogen releases was the most important contributor to ME and FE. Finally, environmental credits from the generation of valuable products, such as heat and compost improved the environmental profile of the system, particularly for CC, OD, POF and FD.

Figure 4 presents the environmental performance of the examined alternative scenarios.

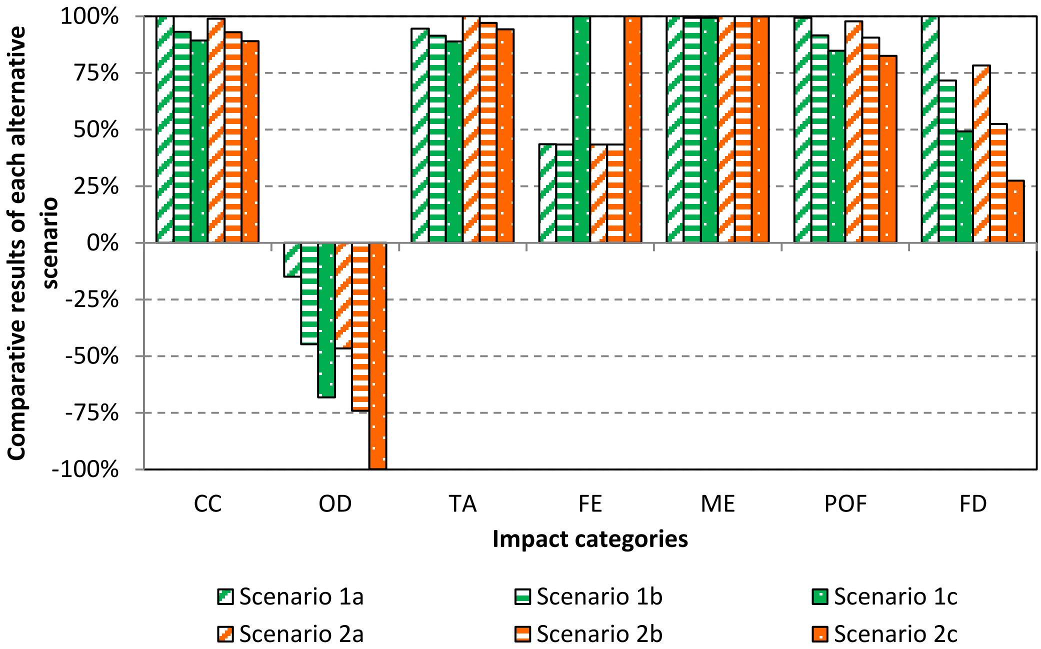

Figure 4. Comparative results of alternative treatment schemes for

In all energy-related impact categories such as CC, OD, POF and FD, the partial recirculation of fermentation liquid to the anaerobic reactor (Scenarios 2a, 2b and 2c) results in better environmental performance compared with the simplest schemes (Scenarios 1a, 1b and 1c). This is attributed to the higher production of biogas and consequently higher credits from the avoided production of heat from natural gas.

Concerning the removal of nitrogen, each process entailed different emissions of nitrous oxide and carbon dioxide, as well as electricity consumption due to aeration requirements. The production of Electric consumed in the process is in this case the main contributor energy-related categories such as CC, OD, POF and FD. Denitrification via nitrate (Scenarios 1a and 2a) requires 30% more aeration than SCND (Scenarios 1b and 2b), while SCND requires 30% more aeration than PN-ANM (Scenarios 1c and 2c). Thus, the best environmental results for these categories were obtained for PN-ANM process.

ME and FE were directly linked with the discharge of the final effluent. The efficiency for nitrogen removal has been considered the same for all denitrifiacion options under assessment. However, the PN-ANM is not able to remove phosphorus from the effluent. This, Scenarios 1c and 2c had 57% more impact in FE.

4. Conclusions

This study examined the environmental performance of the combined management of wastewater and DOW for a small community. The results showed that the production of electricity is the major *hotspot* for almost all impact categories under examination. However, regarding FE and ME, the discharge of the effluent is the main contributor. The production of valuable products, such as biogas and compost enhanced the environmental profile through the contribution of environmental credits. The partial recirculation the fermentation liquid and the application of the PN-ANM process in the SBR identified as the best options from an environmental point of view.

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