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Title: Environmental assessment of decentralised schemes for the integrated management of wastewater and domestic organic waste

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Keywords: Anaerobic treatment; small and decentralised systems; domestic wastewater; short-cut nitrification denitrification; LCA; domestic organic waste

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Cover Letter

Brunel University London
College of Engineering, Design and Physical Sciences
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London, 8th July, 2016

Dear Editor,

We are pleased to submit a new revised version of our manuscript entitled ‘Environmental assessment of decentralised schemes for the integrated management of wastewater and domestic organic waste’ by L. Lijó, S. Malamis, S. González-García, M.T. Moreira, F. Fatone and E. Katsou, to be considered for publication in the Journal of Environmental Management.

We remain at your disposal for anything you may need.

On behalf of all the authors,
Sincerely Yours,

E Katsou

Evina Katsou
Lecturer
Brunel University, London

Replies to reviewer comments

We would like to thank for the comments and suggestions that helped to improve the quality of the manuscript. The authors have agreed for all the changes. Below there is a detailed description of our answers to every comment. At the end of this document, it has been included the manuscript with all the changes marked in red.

In addition, according to the specifications of the editor, the length of the manuscript has been reduced from 6328 to 5624 words (-11%). Figures quality has been improved and tables have been modified. In addition, the manuscript has been revised in detail. Finally, the order of the authors has been modified and the acknowledgements completed.

- Reviewer #1:

The authors should include a complete inventory of these technologies (at least for the main scheme A and B) including all inputs and outputs for each stage considered (e.g. electricity consumption in WWTP, electricity consumption during the composting, gases emissions at each stage, amount of compost applied to land, and so on), if not, the results are not easily interpreted. Specify source of the data (own lab data, real full-scale data, references, etc.)

An inventory table including data for analysis of Schemes A1 and B1 has been incorporated in the revised manuscript. However, since the length of manuscript must be reduced, we included the table as supplementary material (Table S1); a second document is attached in the submission of the revised paper. In addition, a second table in the supplementary material (Table S2) has been included in order to explain how the energy consumption of the system has been computed together with the sources used. In the manuscript, section 2.3. "Inventory data acquisition and assumptions" has been improved and explanations are given for the origin of the data. "The inventory data and detailed description of sources used for the calculation of energy consumption are given as supplementary material (Table S1 and Table S2).

A Figure with the system boundaries including the main inputs and outputs should be included.

Figure 1 has been modified in order to include the inputs and outputs of each step of the main treatment schemes.

Table 1 (or a new table) should include physico-chemical properties of final products (e.g. compost applied to land, final water quality) and not only initial properties of products.

Information for the final products is included in Table 2 “Summary of output parameters for the examined treatment schemes”. In the same table, apart from the amount of methane, we have specified the composition of the final effluent in terms of flow, total solids, COD, N, P as well as the composition of the produced compost in terms of production, TS, C, N and P.

Pag.13, l.35: How the ammonia emissions are estimated? In methodology it can be read, "While other parameters, such the mass reduction and nitrogen losses were calculated based on the findings of Adhikari et al. (2008) and Guo et al. (2012). The electricity consumption, diesel requirements and the methane and nitrous oxide emissions were computed following the methodology described by Boldrin et al. (2009) considering closed composting systems. The carbon dioxide and ammonia emissions during carbon and nitrogen removal were estimated through mass balances". Also, the work from Adhikari deals only with food waste, and the reference from Guo deals with pig waste and not with wastewater. Is there no references dealing with ammonia emissions during sewage sludge composing? Please, give more details about the how these data is obtained, modeled and justify the selection of these assumptions.

The methodology for the estimation of the emissions derived from the composting process has been included in section 2.3. “Inventory data acquisition”. The following part has been added in the revised MS: “Concerning the composting process, average reductions of 45%, 22% and 10% have been respectively considered for mass, carbon and nitrogen according to the findings of Adhikari et al. (2009) and Rihani et al., (2010). Considering closed composting systems, the electricity consumption and diesel requirements are included in the analysis (Fisher, 2006), while methane and nitrous oxide emissions have been calculated following the methodology of Boldrin et al. (2009). Carbon dioxide and ammonia emissions during carbon and nitrogen removal have been estimated through mass balances. According to the study of Colón et al. (2009), the removal efficiency of the biofilter for volatile organic compounds and ammonia are, as average, 63% and 75%, respectively. In addition, other inputs in the system, such as tap water sprayed on the biofilter surface have been taken from Cadena et al. (2009)".

Concerning the literature sources used for modelling the composting system, several studies have been considered. Adhikari et al. (2009) studied the composting of food waste; Rihani et al. (2010) investigated the treatment of urban sludge by aerobic composting. Fisher (2006) examined the impact of different systems for the treatment of the organic fraction of municipal solid waste, including in-vessel and windrow composting. Boldrin et al (2009) reviewed emissions from different composting technologies for the treatment of food waste.

Ammonia from composting units can have a large degree of variability depending of the composting technology and also the off-gases post-treatment (biofiltration, acid scrubber, etc.). If you have modeled the composting process as a closed system (e.g. composting tunnel), usually there is an off-gases treatment with high ammonia removal efficiencies. Please, explain if off-gases treatment is considered, if not, please justify it

In the baseline scheme, a biofilter for the treatment of emissions derived from composting has been included in section 2.2. and 2.3: "Sludge is composted in an enclosed system equipped with a biofilter consisting on wood chips (Colón et al., 2009)" and "According to the study of Colón et al. (2009), the removal efficiency of the biofilter for volatile organic compounds and ammonia are, as average, 63% and 75%, respectively. In addition, other inputs in the system, such as tap water sprayed on the biofilter surface have been taken from Cadena et al. (2009)".

Several assumptions have been done throughout the work. Although maybe out of the scope of this work, it would be nice to include several sensitivity scenarios covering a wide range of assumptions for the main contributors to TA, FE, ME and CC (e.g. ammonia emissions, BNR removal efficiencies, …).

A sensitivity analysis has been included in order to assess the effect of influential factors in the LCA results, giving data on the outcome of the study. A new section has been included for this purpose (section 3.1.3). Specifically, both the influence of the update of the electricity production mix process from ecoinvent ® database and the methodology selected for the calculation of emissions derived from the application of compost have been assessed and included in the revised manuscript: "*A sensitivity analysis has been conducted in order to assess the influence of assumptions that affect the LCA results…*"

In TA, have you modeled H2S emissions from biogas (both direct release and also after biogas combustion in form of SOX?, it could have a non-negligible impact on TA), have you included or considered a desulphuration stage in your set-up?

An anoxic biotrickling filter packed with wood chips for the removal of H_2S present in the biogas has been considered. A number of assumptions such as 0.1% H_2S in the biogas stream, removal efficiency of 75% for the biofilter and finally, the complete oxidation of H_2S to SO_2 in the boiler were taken. In the manuscript, this part has been included in section 2.2 "Description of the treatment schemes" as follows: "The composition of the produced biogas is 60% methane, 39.9% carbon dioxide and 0.1% hydrogen sulphide. The biogas is treated in a biotrickling filter in order to remove hydrogen sulphide with a removal efficiency of 75%. The data used in order to compute this process has been taken from the European LIFE+ project "LIVE-WASTE (LIFE 12 ENV/CY/000544)".

Pag. 2: revise text: "This is because in some are areas …"

This sentence has been removed from the manuscript.

Pag. 10, l.42: Specify ecoinvent version.

We used ecoinvent® database version 3.1. This has been included in the revised manuscript in section 2.3: "The ecoinvent® database (version 3.1) has been used in order to include background data".

Specify the amount of substituted product (e.g. peat and natural gas)

The amount of substituted product has been included in the inventory table (Table S1).

Trucks: Specify what truck (e.g. ecoinvent trucks specifically used for waste collection…), specify travelling distance, etc…

The specific vehicles used for transport requirements, as well as other processes, are described in section 2.3. "Inventory data acquisition and assumptions". The following part has been added: "Specifically, the generation of electricity from the grid (Italian electricity medium voltage), heat from natural gas (condensing modulating boiler <100 kW) and peat production have been taken from Dones et al. (2007). Data concerning the production of chemicals, such as chlorine, sodium hypochlorite and polyelectrolyte have been included according to the study of Althaus et al. (2007). In addition, a lorry of 21 metric tons has been used to deliver DOW into the treatment facility and an agricultural tractor and trailer have been used to transport straw to the treatment plant and the compost for land application (Spielmann et al., 2007). Finally, waste generated in the treatment process is disposed in a sanitary landfill (Doka, 2007)". The transport distances are detailed in Table S1 of the supporting material.

Boldrin et al., 2009 is not included in the reference list

Boldrin et al (2009) has been included in the reference list.

- Reviewer #2:

Keywords: please consider to substitute: "environmental profile" with "LCA"

“LCA” has been included in the keywords instead of “environmental profile”

Introduction: Pag 2, please consider to substitute: "However, this practise is not feasible in many places, or not the most cost-effective alternative in some cases." WITH "However, due to morphological conditions (Libralato et al., 2012), this solution is not feasible in many areas, or not the most cost-effective one".

The sentence has been modified accordingly.

Introduction: Pag 2, please consider to substitute: "Therefore, new approaches are needed to develop sustainable water management, especially in areas with water shortages (Gikas and Tchobanoglous, 2009)" WITH "A different approach, focused on decentralized systems, can be necessary to develop sustainable water management for small communities, especially in areas affected by severe water shortages (Gikas and Tchobanoglous, 2009)"

The sentence has been modified.

Introduction: Pag 2, please remove "This is because in some are areas decentralisation is the only suitable option due to morphological conditions (Libralato et al., 2012).

The sentence has been removed.

Introduction: Pag 3, row 2 please consider to substitute "reactors have several advantages" WITH "reactors show several advantages"

The modification has been made.

Introduction: Pag 3, row 3 please consider to substitute "less" with "lower"

The sentence has been corrected.

Introduction: Pag 3, row 9 please consider to substitute " type of treatment" WITH "treatment"

The modification has been made.

Introduction: Pag 3, row 17 please consider to substitute " of organic matter and suspended solids" WITH "" of organic matter and suspended solids removal"

The modification has been made.

Introduction: Pag 3, row 28 please consider to substitute "Decentralised management increases reuse opportunities, since the effluent is available near the potential points of use and decreases the costs of reclaimed water distribution systems (Hophmayer-Tokich, 2000)." WITH "Decentralised management increases reuse opportunities, since the effluent is often available close to the potential points of use so decreasing the costs of reclaimed water distribution systems

The sentence has been modified accordingly.

Introduction: Pag 3, row 33 please consider to substitute "Despite the fact that the reclaimed water which is rich in nutrients can be beneficial for plants it also needs to comply with the existing National or other reuse legislation." WITH "Despite its important content in nutrients, that can be beneficial for the cultivated products, the reclaimed water needs to comply with extremely severe national or regional regulation often discouraging or even preventing their legal utilization"

The modification has been made.

Introduction: Pag 3, row 40 please introduce "allowed" after concentration

The modification has been made.

Introduction: Pag 4, row 33 please consider to substitute "Another advantage is related with the reduction" WITH " A further advantage is related to the reduction "

The sentence has been finally removed.

Introduction: Pag 4, row 50 please consider to substitute "DOW" with Waste

The modification has been made.

Highlights

- Environmental analysis of sewage & organic waste co-treatment in a small community
- DOW was used as carbon source for BNR and biogas increase in anaerobic treatment
- Anaerobic treatment resulted in better performance in terms of energy consumption
- BNR reduces the environmental impact for eutrophication related categories
- Implementation of FWDs in 50% of households increases the environmental impact

Environmental assessment of decentralised schemes for the integrated management of wastewater and domestic organic waste

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Abstract

This study assesses from an environmental perspective two alternative configurations for the combined treatment of wastewater and domestic organic waste (DOW) in a small and decentralised community having a population of 2,000. The applied schemes use an upflow anaerobic blanket (UASB) as core treatment process. Scheme A integrates membranes with the anaerobic treatment, while in Scheme B biological removal of nutrients in a sequencing batch reactor (SBR) is applied as a post treatment for the UASB effluent. In energy-related categories, the main contributor is electricity consumption (producing 18-50% of the impacts); whereas in terms of eutrophication-related categories, the discharge of the treated effluent arises as a major hotspot (with 57-99% of the impacts). Scheme B consumes 25% more electricity and produces 40% extra sludge than Scheme A, resulting in worse environmental results for those energy categories. However, the environmental impact due to the discharge of the treated effluent is 75% lower in eutrophication categories due to the removal of nutrients. In addition, the quality of the final effluent in Scheme B allows its use for irrigation (9.6 mg N/L and 2 mg P/L) expanding its adoption potential at a wider scale. Additionally, the study shows the environmental feasibility of the use of food waste disposers for DOW collection in different integration rates.

Keywords

Anaerobic treatment; small and decentralised systems; domestic wastewater; short-cut nitrification denitrification; LCA

1. Introduction

Historically, centralised wastewater treatment facilities have played an important role in water management (Gikas and Tchobanoglous, 2009). However, due to morphological conditions (Libralato et al., 2012), this solution is not feasible in many areas, or not the most cost-effective one. A different approach, focusing on decentralised systems, must be applied to develop sustainable water management for small communities, especially in areas affected by severe water shortages (Gikas and Tchobanoglous, 2009). There are many small communities where sustainable water and waste management solutions should be applied. For example, in Italy more than 9,000 wastewater treatment plants (WWTPs) serve less than 2,000 population equivalent (PE).

Among the different available technologies for decentralised wastewater treatment, the upflow anaerobic sludge blanket (UASB) process has several advantages compared to aerobic treatment, such as reduced capital investment, lower energy requirements, limited sludge generation and biogas production for energy recovery (Chernicharo, 2006). Although this technology accomplishes significant removal of organic matter, the treated effluent still contains significant concentration of suspended solids, while nutrients are practically not removed (Malamis et al., 2013). To meet the requirements of the European Union Directive 91/271/EEC concerning the discharge of the treated urban wastewater to water recipients further treatment of the UASB effluent is required for the further decrease of organic matter and suspended solids and for nutrients removal, if required. The biological process can be coupled with membranes in an anaerobic membrane bioreactor (AnMBR) for the solid/liquid separation. The application of the AnMBR technology can convert WWTPs into resource (i.e. energy, reclaimed water rich in nutrients) recovery facilities. This process has lower energy requirements than the aerobic membrane bioreactor (MBR) and produces less amount of sludge. The main barriers for the application of AnMBRs for domestic wastewater treated are related with the operating cost for membrane fouling control and mitigation (Li et al., 2013).

Decentralised wastewater management increases reuse opportunities, since the treated effluent is often available close to the potential sites of use, avoiding the cost related with reclaimed water distribution systems (Hophmayer-Tokich, 2000). Despite its important content in nutrients, which can be beneficial for the cultivated products, the reclaimed water often needs to comply with strict national or regional regulations concerning its reuse (Norton-Brandão et al., 2013). For instance, the Italian Decree for water reuse (Decreto Ministeriale n. 185, 2003) sets up maximum concentrations of phosphorus and nitrogen in the reclaimed water (2 mgP/L and 15 mgP/L, respectively). In this case, biological and/or physicochemical post-treatment processes must be applied to remove or to recover nutrients from the anaerobically treated effluent such as ammonia stripping (Walker et al., 2011), struvite precipitation (Battistoni et al., 2006), biological nutrient removal (BNR) (Frison et al., 2013a). Nitritation/denitritation and denitrifying phosphorus removal via nitrite (DPRN) has recently gained attention due to several advantages over the conventional via nitrate pathway (Gustavsson, 2010; Zhang et al., 2010).

The integration of domestic organic waste (DOW) within the decentralised wastewater management scheme is an option that can contribute to the diversion of DOW from landfilling, in accordance to the Landfill Directive (Directive 1999/31/EC, 1999). DOW can be source of short-chain fatty acids (external carbon source) that are required for the biological nitrogen and phosphorus removal (Frison et al., 2013b). Alternatively, the fermented DOW can be applied in the anaerobic process in order to increase the organic loading rate (OLR) and thus, the biogas production. Alternative systems exist for DOW collection and delivery into the treatment facility. Food waste disposers (FWDs) are applied in several countries (e.g. USA, Canada, Brazil, Japan and Australia) for the integrated management of domestic wastewater and DOW (Battistoni et al., 2007). The use of FWDs reduces the frequency of waste transport and generates less odours compared to the conventional separate waste collection schemes (Marashlian and El-Fadel, 2005). However, a number of important drawbacks, such as additional energy requirements, use of extra tap water for dragging the waste mixed with the wastewater, increased organic loads in the sewerage system and the WWTP burdens their feasibility (Marashlian and El-Fadel, 2005).

The assessment of the treatment systems from an environmental life cycle perspective can improve the environmental profile of the decentralised treatment schemes. The current study evaluates the environmental performance of alternative decentralised schemes for wastewater and DOW co-treatment in a small and decentralised community of 2,000 PE following a Life Cycle Assessment (LCA) approach.

2. Materials and methods

2.1. Goal and scope definition

The selection of the main configuration for combined wastewater and DOW treatment was based on the results of our previous study (Katsou et al., 2014), taking into consideration economic criteria (cost reduction), legislative aspects for the treated effluent quality and DOW management and topographical factors (i.e. characteristics of small community in terms of waste collection). The decentralised schemes include the anaerobic treatment of wastewater, a fermentation unit in order to produce short-chain fatty acids and a composting unit to stabilise the sludge produced from the process. Scheme A includes an AnMBR, while Scheme B applies SBR for the BNR via nitrite. Different waste collection systems are considered within each configuration. The functional unit (FU) is the service provided by the system, which includes the management of the wastewater and DOW produced by 2,000 inhabitants per day.

2.2. Description of the treatment schemes

Each treatment scheme applies screening prior to the anaerobic process. The organic loading rate (OLR) of the UASB in Chemical Oxygen Demand (COD) terms ranges from 1.5 to 2.5 kg COD/m^3·d, with a hydraulic retention time (HRT) of 8 h and an upflow velocity of 1 m/s (Katsou et al., 2014). The composition of the produced biogas is 60% methane, 39.9% carbon dioxide and 0.1% hydrogen sulphide. The biogas is treated in a biotrickling filter in order to remove hydrogen sulphide with a removal efficiency of 75%. The data used in order to compute this process have been taken from the European LIFE$^+$ project "LIVE-WASTE (LIFE 12 ENV/CY/000544). Finally, the biogas is burnt in a boiler and is used to cover the heat requirements of the fermentation tank. The received DOW is grinded and then acidogenic fermentation is performed to produce volatile fatty acids (VFA). The HRT is between 5 and 6 days and the OLR in terms of volatile solids (VS) is 10 kg VS/m^3·d. After a solid/liquid separation, the VFAs are fed to the UASB in order to increase the OLR and the biogas generation (Scheme A) and/or are used as carbon source to promote the BRN in the SBR (Scheme B). The separation of the fermented effluent and the excess sludge from the UASB is performed using a screw-press. The produced sludge is mixed with a bulking agent (straw) in order to provide suitable porosity and optimum carbon to nitrogen ratio (25:1-35:1) for the composting process to take place. Sludge is composted in an enclosed system equipped with a biofilter consisting on wood chips (Colón et al., 2009). The compost is applied in agricultural land as a soil conditioner.

Scheme A: The total liquid stream produced from the screw-press is fed to the UASB. Consequently, the OLR increases from 1.8 to 2.4 kg COD/m^3·d, resulting in increased biogas production (0.35 m^3 CH_4/kg $COD_{removed}$). Coupling the treatment scheme with membranes results in the production of a final effluent free of total suspended solids (TSS).

Scheme B: The liquid stream produced after the separation step is fed to the SBR in order to provide the required carbon source for nutrient removal. The UASB effluent which is fed to the SBR is characterised by a very low COD/N ratio (2.3 kg COD/kg N) and even lower ratio of readily biodegradable COD to nitrogen (rbCOD/N), which is not enough to remove nutrients. The SBR has a solids retention time (SRT) of 18 days and a volumetric nitrogen loading rate (vNLR) of 0.19 kg N/$m^{3\cdot}$d. The SBR operates with the following sequence: feeding (0.17 h), aerobic phase (1.8 h), anoxic phase (0.81 h), sedimentation (0.33 h) and discharge (0.17 h). The flowcharts of the examined configurations are presented in Figure 1. As mentioned, each of treatment schemes has also been evaluated considering different collection systems.

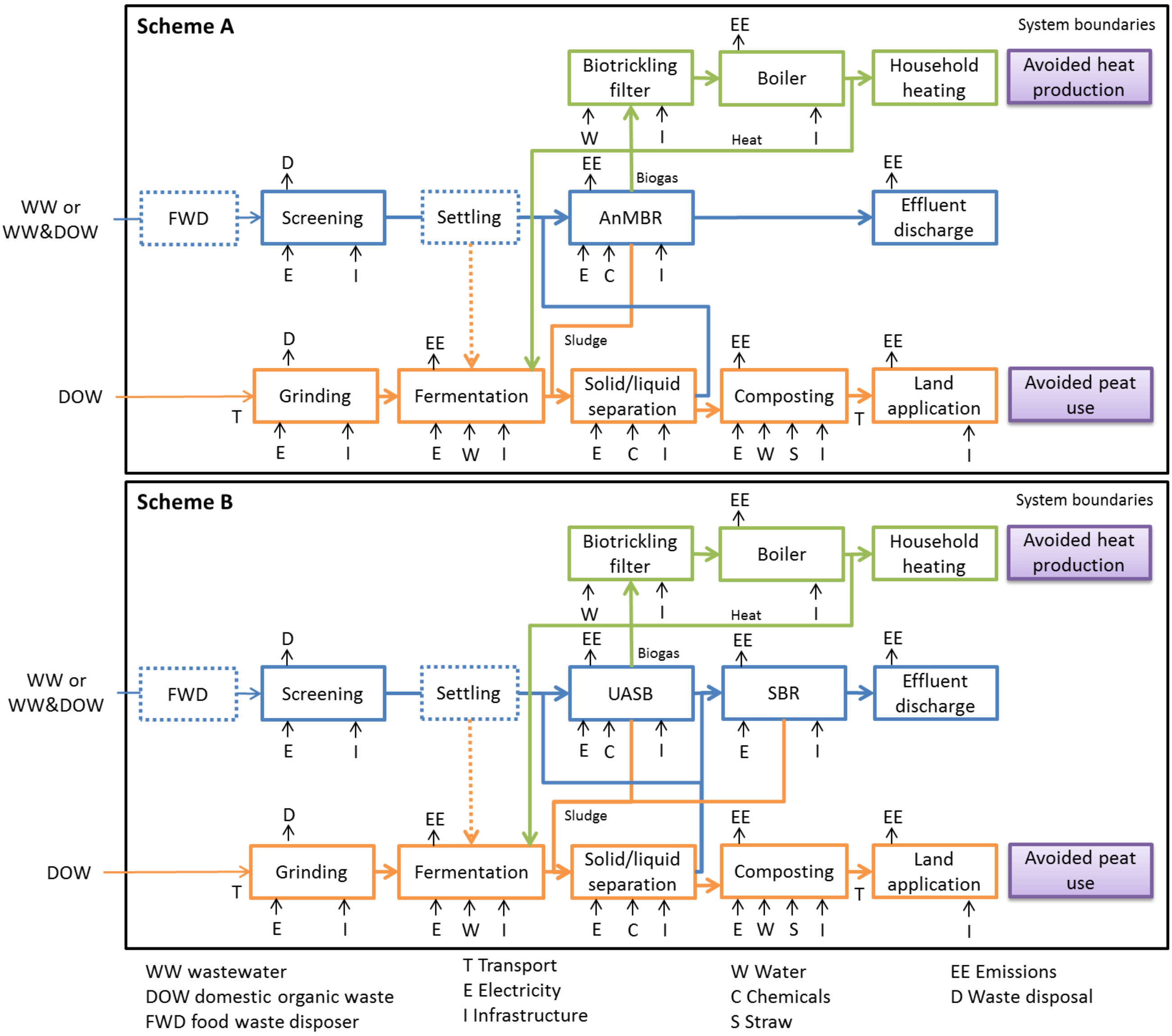

Figure 1. Main configurations for the management of wastewater and DOW at decentralized level. Dotted processes are only included in Schemes A2, A3, B2 and B3.

Schemes A1 and B1 perform separate waste collection. Wastewater is collected by the sewerage system and is pumped directly from households to the screening unit of the WWTP.

DOW is separately collected at household level in plastic bags and is transported by trucks to the plant. Then, DOW is grinded and fed to the fermentation unit.

Schemes A2 and B2 include the integration of FWDs in 50% of the households of the community. Both electricity and tap water are supplied to pump the combined stream of wastewater and DOW to the WWTP (Evans et al., 2010). Primary settling is applied after screening to separate the primary sludge from the primary effluent. Primary sludge is fed to the fermentation unit from the liquid stream that is sent to the UASB. The remaining 50% of DOW is delivered by trucks to the plant and is grinded before fermentation.

Schemes A3 and B3 include complete (100%) integration of FWDs in the community. DOW generated in households is pumped together with the wastewater. A primary settler is applied after screening of combined sewage and DOW and then the primary effluent is sent for anaerobic treatment. This scheme is characterised by large water and electricity consumption. Nevertheless, the use of plastic bags for waste collection and the transport of DOW by truck is avoided.

2.3. Inventory data acquisition

The development of the inventory is mainly based on real data obtained from the operation of a pilot scale UASB-SBR system at the premises of the University of Verona (Katsou et al., 2014). In order to simulate the whole treatment scheme (Figure 1), mass balances have been developed for organic matter (COD and volatile suspended solids) and nutrients (N and P). A small percentage (around 1.5%) of the biogas that is produced in the anaerobic process is released to the atmosphere due to leakages in valves and pipes. The assumed thermal efficiency of the boiler is 90%. The air requirements of the SBR have been calculated according to Tchobanoglous et al. (2014). Nitrous oxide emissions released from the biological processes have been considered and estimated according to Frison et al. (2015). Concerning the maintenance of the AnMBR, it has been assumed that the membrane is cleaned four times per year, including chemical consumption (sodium hypochlorite).

The calculation of the main parameters for the fermentation process is based on previous studies; e.g. HRT from Traverso et al. (2000), OLR from Lee et al. (2014), total solids (TS) from Frison et al. (2013b) and COD and TS losses in fermentation from Battistoni et al. (2007). The emissions of carbon dioxide, methane and ammonia are also taken into account. Specifically, it has been considered that 90% of the carbon that is lost in the fermentation tank is released to the atmosphere as carbon dioxide and 10% as methane, while the total nitrogen loss is in the form of ammonia. The solid/liquid separation has been modelled considering the performance parameters from the work of Albertson et al. (1991) and Battistoni et al. (2007). Concerning the composting process, average reductions of 45%, 22% and 10% have been respectively considered for mass, carbon and nitrogen according to the findings of Adhikari et al. (2009) and Rihani et al., (2010). Considering closed composting systems, the electricity consumption and diesel requirements are included in the analysis (Fisher, 2006), while methane and nitrous oxide emissions have been calculated following the methodology of Boldrin et al. (2009). Carbon dioxide and ammonia emissions during carbon and nitrogen removal have been estimated through mass balances. According to the study of Colón et al. (2009), the average removal efficiency of the biofilter for volatile organic compounds and ammonia are 63% and 75%, respectively. In addition, other inputs in the system, such as tap water sprayed on the biofilter surface have been considered from Cadena et al. (2009). The emitted gases from compost application on land are computed using the emission factors included in the study of Bruun et al. (2006). The consumption of electricity along the different stages of each treatment scheme has been calculated according to Tchobanoglous et al. (2014). In terms of infrastructure, the required volume of concrete for each reactor has been estimated considering typical dimensions that are usually met for this type of equipment and size of

WWTP. Other construction materials (e.g. aluminium, polyethylene and water) are included in the inventory (Foley et al., 2010).

Concerning the separate DOW collection, plastic bags are computed as described in the study of Blengini (2008). Information for the additional use of electricity for the operation of FWDs and the required tap water has been obtained from Evans et al. (2010) and Rosenwinkel and Wendler (2001), respectively.

The ecoinvent® database (version 3.1) was used in order to include background data. Specifically, the generation of electricity from the grid (Italian electricity medium voltage), heat from natural gas (condensing modulating boiler <100 kW) and peat production have been taken from the study of Dones et al. (2007). Data concerning the production of chemicals, such as sodium hypochlorite and polyelectrolyte have been included according to the study of Althaus et al. (2007). In addition, a lorry of 21 tonnes was used to deliver DOW into the treatment facility and an agricultural tractor and trailer were used to transport straw to the treatment plant and the compost for land application (Spielmann et al., 2007). Finally, waste generated in the treatment process was assumed to be disposed in a sanitary landfill (Doka, 2007). Additionally, a sensitivity analysis was performed in order to assess the effect of the main assumptions in the LCA results.

Table 1 and Table 2 summarize the main inputs and outputs for the examined treatment schemes. The inventory data and detailed description of sources used for the calculation of energy consumption are given as supplementary material (Table S1 and Table S2).

Table 1. Summary of input parameters taken into account for the treatment schemes

Input flow	**Units**	**Separate collection**	**50% separate collection 50% FWDs**	**100% FWDs**
Wastewater flow	m^3/d	400	-	-
COD	mg/L	600	-	-
N	mg/L	60	-	-
P	mg/L	9	-	-
DOW treatment	kg/d	500	250	-
COD	mg COD/ gTS	1200	1200	-
N	mg N/ gTS	25	25	-
P	mg P/ gTS	3	3	-
WW + 50% DOW	m^3/d	-	405	-
COD	mg/L	-	828	-
N	mg/L	-	64	-
P	mg/L	-	9.6	-
WW + DOW	m^3/d	-	-	409
COD	mg COD/gTS	-	-	1051
N	mg/L	-	-	69
P	mg/L	-	-	10

Table 2. Output parameters for the examined treatment schemes

Parameter	**Unit**	**Scheme A1**	**Scheme A2**	**Scheme A3**	**Scheme B1**	**Scheme B2**	**Scheme B3**
Methane production	m^3/d	96	93	100	61	52	59
Heat production	kWh/d	897	873	940	570	485	555
Final effluent							
Flow	m^3/d	402	404	408	401	404	408
TS	mg/L	0	0	0	26	23	17
COD	mg/L	80	78	83	41	67	70
N	mg/L	63	64	66	9.6	9.9	10
P	mg/L	8.5	8.9	9.2	1.95	1.83	1.15
Compost production	kg/d	300	406	395	616	730	717
TS	%	25	25	25	39	36	36
C	g/kg TS	465	465	468	686	653	657
N	g/kg TS	19	19	14	31	29	27
P	g/kg TS	5.4	5.2	4.6	14	17	17

2.4. Impact assessment methodology

The ReCiPe Midpoint H methodology (Goedkoop et al., 2009) was applied to identify the systems *hotspots* that are mainly responsible for environmental burdens. The following impact categories have been considered: climate change (CC) in order to report the contribution to the greenhouse effect; ozone depletion (OD) as an indicator of the contribution to the ozone hole; terrestrial acidification (TA) in order to measure the influence on the acid rain phenomenon; freshwater eutrophication (FE) to quantify the potential enrichment of nutrients in surface water; marine eutrophication (ME) to analyze marine water enrichment in nutrients; photochemical oxidant formation (POF) to depict the formation of reactive chemical compounds, such as ozone in the troposphere and fossil depletion (FD) as an indicator of the reduction of fossil resources.

3. Results and discussion

3.1. Environmental performance of domestic wastewater and DOW management scheme

3.1.1 Schemes A1 and B1: main configurations

Table 3 summarises the LCA characterisation results for the two main configuration schemes per FU. In addition, Figure 2 shows the relative contributions of the core processes for each treatment scheme. Positive values indicate environmental burdens, whereas negative values reveal environmental benefits

Table 3. Environmental profile of the treatment systems

Category	Unit	Scheme A1	Scheme B1
CC	kg CO_2 eq	37.9	276
OD	mg CFC-11 eq	$6.5 \cdot 10^{-6}$	$1.6 \cdot 10^{-5}$
TA	kg SO_2 eq	0.48	1.44
FE	kg P eq	3.42	0.84
ME	kg N eq	26.1	6.67
POF	kg NMVOC	0.30	0.41
FD	kg oil eq	-25.7	13.5

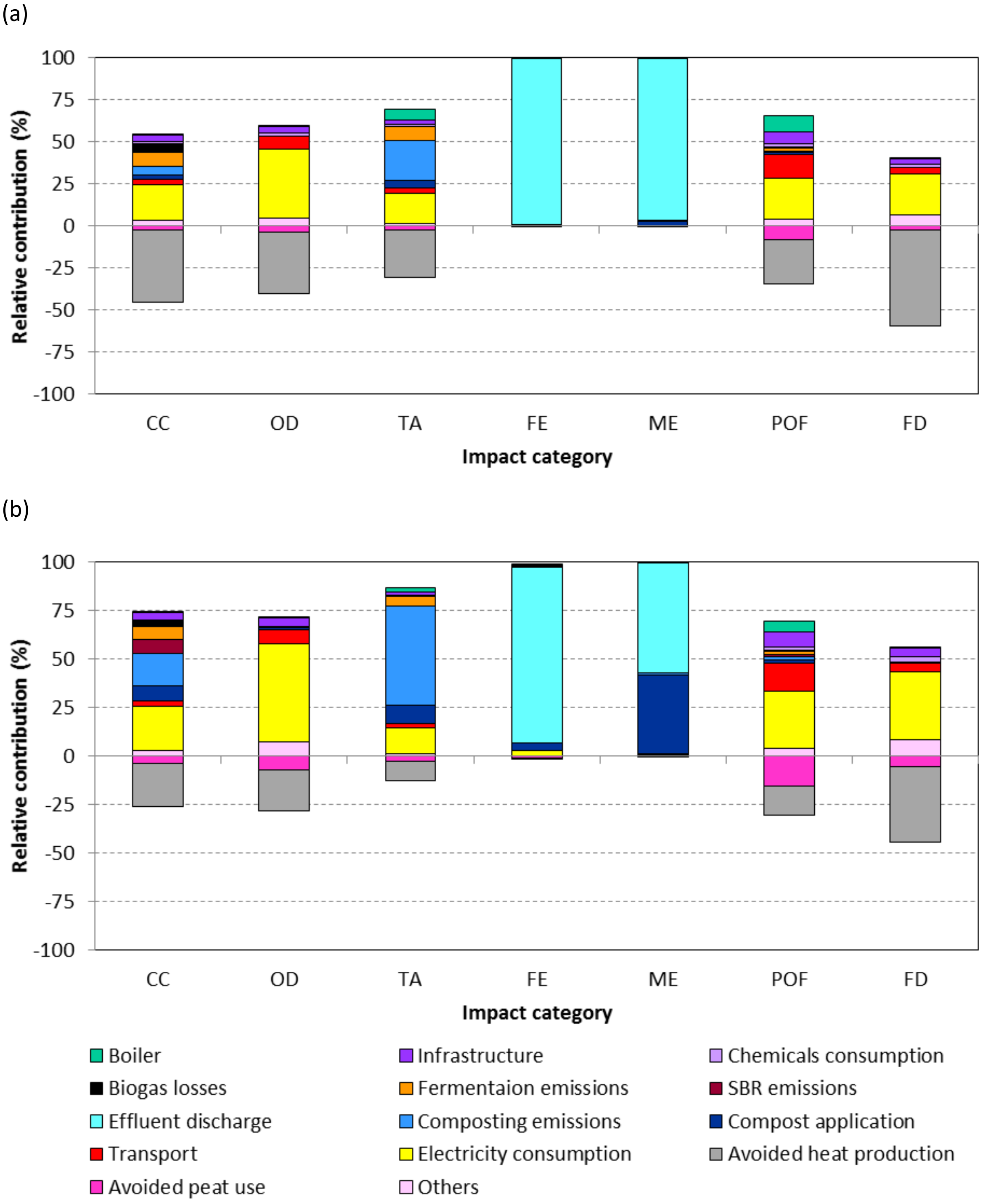

Figure 2. Contribution of each process involved in Scheme A1 (a) and B1 (b)

Scheme A1 performs better compared to Scheme B1 in terms of CC, OD, POF and FD. Electricity consumption and avoided heat production from natural gas are identified as the most influential parameters, with contribution ranging from 21-50% and 21-56%, respectively for the different impact categories. Scheme B1 consumes more electricity than Scheme A1 in order to treat the same amount of sewage and DOW, mainly due to aeration requirements during the aerobic phase of the SBR. In addition, in Scheme A1, biological nutrient removal is not practiced; thus the entire available carbon source of the fermentation process is fed to the AnMBR. The latter results in enhanced biogas production and thus, increased energy generation; thus, more environmental credits are obtained due to the avoided heat production from natural gas.

Concerning TA, the main contributor is ammonia emissions, mainly derived from the production and the land application of the compost. Composting emissions account for 20% in Scheme A1 and 48% in Scheme B1; the difference is related with the amount of sludge produced. Scheme B1 that includes SBR generates higher sludge quantities and consequently, higher ammonia emissions during the composting process. In addition, higher amount of compost is produced, resulting in higher ammonia emission levels when compost is applied on land as a soil conditioner. Concerning the eutrophication-related categories (FE and ME), the results are directly affected by the concentration of TP and TN in the final effluent that is discharged. Specifically, phosphorous affects FE, while nitrogen affects ME. As explained before, Scheme B1 that applies BNR, obtains better environmental results for these two impact categories due to the lower nutrient concentration of the treated effluent that is discharged. It is important to highlight that the removal of nutrients in Scheme B1 results in a high quality treated effluent that meets the requirements for water reuse in Italy (Decreto Ministeriale n. 185, 2003). The reuse of the effluent can enhance the environmental performance of Scheme B1.

3.1.2 Schemes A1-A3 and B1-B3: the effect of the DOW management scheme

Figure 3 summarises the results for all the examined schemes, considering three different waste collection systems.

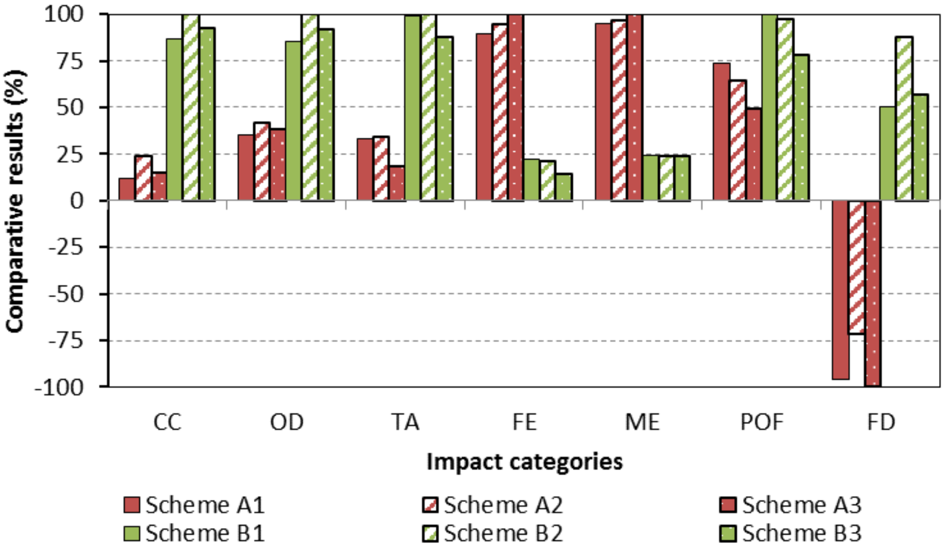

Figure 3. Environmental performance of the decentralised treatment schemes

The partial implementation of FWDs (50%) integrated with the collection of DOW from the households that do not have a FWD exhibits the worst environmental performance in terms of CC, OD, TA and FD (schemes A2 and B2). This waste collection practice results in less heat production and thus lower environmental credits (Table 2), affecting CC, OD and FD. In addition, FWDs produce more sludge and thus, more methane and nitrous oxide emissions are generated from the composting unit and the compost application as a soil conditioner. Partial implementation of FWDs means that in households where FWDs are not installed, DOW needs to be collected by trucks and sent to the treatment facility. Therefore, this scheme is burdened by the technology/infrastructure for the FWDs (i.e. settler after sewage screening) and the separate DOW collection and transportation (i.e. waste collection bins and trucks). In terms of TA, the differences among schemes are attributed to differences in the quantities of the produced sludge, due to ammonia emissions resulting from the composting process and from the final use of the compost. Therefore, the worst behaviour of Schemes B1, B2, B3 in terms of TA is the related to the higher amount of sludge generated compared to Schemes A1, A2 and A3. The application of nutrient removal via nitrite in the SBR results in higher sludge production compared to the anaerobic processes due to the much higher biomass yield of the aerobic/anoxic bioprocesses. A different behaviour is observed in POF; the separate waste collection (Schemes A1 and B1) exhibits higher environmental impact than the alternative options based on partial or total implementation of FWDs (Schemes A2, B2, A3 and B3). This is mainly due to the environmental burdens related to the collection and transport of waste to the treatment facility by a municipal solid waste truck and the use and disposal of plastic bags. The application of different waste collection approaches in Scheme B does not significantly affect the eutrophication related impact categories.

3.1.3 Sensitivity analysis

A sensitivity analysis has been conducted in order to assess the influence of assumptions that affect the LCA results. The sensitivity analysis is performed for the main configurations: Scheme A1 and B1.

Electricity production. Due to the importance of electricity consumption for the LCA results, a sensitivity analysis regarding the production of the mix of electricity in Italy has been performed. In the baseline scenario, the medium-voltage electricity profile of Italy has been taken from the ecoinvent® database (Dones et al., 2007); while, in the ‘improved’ scenario it has been updated using the data for the average electricity production and import/export data of Italy in 2014 (Terna Rete Italia, 2015). The lower dependence on fossil fuels, such as natural gas (from 47% to 29%) of the updated electricity profile compared with the previous one has a positive effect in the environmental results. Specifically, the highest improvement is observed in impact categories such as CC, OD, POF and FD with average reductions of 45 kg CO_2 eq/FU, $5.5 \cdot 10^{-6}$ kg CFC-11 eq/FU, 0.08 kg NMVOC/FU and 12 kg oil eq/FU, respectively.

Compost application on land. Several methodologies have been reported in the literature for the estimation of emissions derived from the application of organic substrates in agriculture. In the baseline scenario, the emission factors reported by Bruun et al. (2006) have been used. In Chapter 11 of the report "Guidelines for National Greenhouse Gas Inventories" (IPCC, 2006), another methodological approach is presented. In the latter case, ammonia emissions are higher, while nitrous oxide and nitrate emissions are slightly inferior. As a result, the whole environmental profile of the examined schemes is improved in terms of CC (between 6% and 10%) and ME (up to 4%), while the environmental impacts related with TA are 1.8 and 2.3 times higher for Schemes A1 and B1, respectively, compared with the results of the baseline case.

3.2. Comparative evaluation of the current and other LCA based studies

The results of this work are in agreement with previous LCA studies for wastewater treatment. However, only qualitative comparison can be performed, since the schemes examined in our work include the treatment of wastewater together with DOW. Hospido et al. (2004) assessed the potential environmental impacts that are associated with a municipal WWTP designed for 90,000 PE. The discharge of the treated effluent and land application of sludge were the main environmental hotspots of the treatment system. Gallego et al. (2008) analysed the environmental results of alternative technologies for wastewater treatment in small communities of less than 20,000 PE. Both the discharge of the treated effluent and the disposal of sewage sludge were identified as the most important environmental hotspots due to the presence of nutrients and heavy metals, respectively. The environmental and economic performance of 24 WWTPs was evaluated in the study of Rodriguez-Garcia et al. (2011). Nutrient emissions in the treated effluent were again the main hotspot for the eutrophication related categories, while electricity consumption for climate change.

Furthermore, LCA has been applied for the comparison of alternative schemes that apply integrated processes for organic waste and sewage sludge management. Nakakubo et al. (2012) compared the conventional incineration of food waste with the separate treatment of sewage sludge against the anaerobic co-digestion of both waste streams, examining different processes for the digestate treatment. The authors demonstrated that from an environmental point of view, the combined management of both waste streams performed better than the separate scheme. Righi et al. (2013) analysed the environmental profile of decentralised sewage sludge and DOW management through anaerobic co-digestion.

3.3. Applicability of configurations for integrated DOW and sewage management

The selection of the most suitable treatment configuration (Scheme A or B) depends on the specific characteristics of the small community and the final use of the treated effluent. When the final purpose is the treated effluent discharge into water recipients, the treated water should meet the limits set by the EU legislation for urban wastewater treatment (Directive 91/271/EEC, 1991). In the case of a decentralised wastewater treatment plant serving a community ≥ 2,000 PE, restrictions for biochemical oxygen demand (BOD_5 - 25 mg/L), COD

(125 mg/L) and TSS (35 mg/L) are set. However, the absence of limits for TP and TN allows the application of the scheme that includes AnMBR.

The reuse of the final effluent for agricultural purposes limits the application of the system. The Italian Decree regulates water reuse of the treated effluent considering parameters, such as salinity, pathogenicity, nutrients, heavy metals and micropollutants (Decreto Ministeriale n. 185, 2003). The maximum allowable concentrations of phosphorus and nitrogen in the treated effluent are 2 mg/L, and 15 mg/L respectively. Thus, the effluent from the UASB reactor requires post-treatment in order to reduce the nutrients level. In this case, since BNR must be applied, the second treatment configuration is suitable.

4. Conclusions

The environmental performance of alternative configurations has been examined for the combined treatment of wastewater and DOW in a small and decentralised community of 2,000 PE. Anaerobic treatment coupled with membrane filtration or BNR is the core process for all the examined configurations. The effect of DOW collection and co-treatment with sewage in the plant is considered in the environmental analysis. Electricity consumption is the main contributor to CC, OD, POF and FD, while heat production from biogas has a positive impact. Ammonia emitted during the composting process significantly contributes to TA. The discharge of the treated effluent affects FE and ME due to phosphorus and nitrogen emissions. The implementation of BNR reduces the impact for the eutrophication related categories (FE and ME). However, it results in worst environmental results for CC, OD, TA, POF and FD due to high energy requirements and significant sludge production. Among all the examined waste collection alternatives, partial implementation of FWDs in 50% of the households exhibited the worst environmental profile due to lower biogas and higher sludge production and due to the need to include both DOW collection and transport infrastructure as well as FWDs.

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Supplementary Material

Environmental assessment of decentralised schemes for the integrated management of wastewater and domestic organic waste

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Table S1. Global inventory data per functional unit for Schemes A1 and B1

Inputs from Technosphere				
	Scheme A1		*Scheme B1*	
Materials				
Wastewater	400	m^3	400	m^3
DOW	500	kg	500	kg
Polyethylene bags	3.60	kg	3.60	kg
Concrete	0.035	m^3	0.035	m^3
Chlorine (AnMBR)	$5.7 \cdot 10^{-2}$	kg		
Sodium hypochlorite (AnMBR)	$1.4 \cdot 10^{-4}$	kg		
Polyelectrolite (Solid/liquid separation)	2.86	kg	4.23	kg
Tap water (Biotrickling filter)	20.89	L	13.29	L
Tap water (Fermentation)	1,583	L	1,583	L
Tap water (Composting)	34.00	L	60.49	L
Diesel (Composting)	1.63	kg	3.35	kg
Tractor (Land application)	300	kg	616	kg
Transport				
Lorry (DOW collection)	10,000	kg·km	10,000	kg·km
Tractor (Straw transport)	1,000	kg·km	6,000	kg·km
Tractor (Compost transport)	600	kg·km	1232	kg·km
Energy				
Electricity	173	kWh	226	kWh
Outputs to Technosphere				
	Scheme A1		*Scheme B1*	
Products				
Heat (for heating)	868	kWh	540	kWh
Effluent (to discharge)	402	m^3	401	m^3
Compost (to land)	300	kg	616	kg
Avoided products				
Heat from natural gas	868	kWh	540	kWh
Peat	300	kg	616	kg
Wastes				
Landfill	15.6	kg	15.6	kg

Table S1. Global inventory data per functional unit for Schemes A1 and B1 (cont)

Outputs to Environment				
	Scheme A1		*Scheme B1*	
Emissions to air				
From biogas losses				
Methane, biogenic	0.95	kg	0.60	kg
Carbon dioxide, biogenic	1.74	kg	1.12	kg
Hydrogen sulphide	$8.1\cdot10^{-4}$	kg	$5.2\cdot10^{-4}$	kg
From the boiler				
Carbon dioxide, biogenic	138.4	kg	88.0	kg
Methane, biogenic	0.013	kg	0.009	Kg
Carbon monoxide, biogenic	0.069	kg	0.044	kg
Nitrogen oxides	0.079	kg	0.050	kg
Nitrous oxide	0.002	kg	0.002	kg
NMVOC	0.001	kg	$9.5\cdot10^{-4}$	kg
Sulfur dioxide	0.085	kg	0.054	kg
From the SBR				
Nitrous oxide			0.06	kg
Ammonia			$4.1\cdot10^{-4}$	Kg
Carbon dioxide, biogenic			75.5	kg
Methane, biogenic			1.15	kg
From the fermentation tank				
Methane, biogenic	1.70	kg	1.70	kg
Carbon dioxide, biogenic	43.99	kg	43.99	kg
Ammonia	0.08	kg	0.08	kg
From the composting unit				
Methane, biogenic	0.15	kg	0.61	kg
Carbon dioxide, biogenic	40.8	kg	163.7	kg
Nitrous oxide	0.06	kg	0.24	kg
Ammonia	0.06	kg	0.22	kg
From the agricultural application of the compost				
Nitrous oxide	0.05	kg	0.18	kg
Ammonia	0.04	kg	0.15	g
Emissions to water				
From the discharge of the effluent				
COD	32.0	kg	16.35	kg
Suspended solids	0	kg	10.35	kg
Nitrogen, total	25.3	kg	3.85	kg
Phosphorus, total	3.4	kg	0.78	kg
From the agricultural application of the compost				
Nitrate	0.91	kg	3.44	kg
Phosphate	0.01	kg	0.11	kg

Table S2. Inventory sources for energy consumption

Unit	**Energy consumption**	**Source**
Wastewater pumping	0.0385 kWh/$m^3_{wastewater}$	Tchobanoglous et al. (2014)
Sludge pumping	0.0008 kWh/$m^3_{wastewater}$	Tchobanoglous et al. (2014)
Screening	0.0004 kWh/$m^3_{wastewater}$	Tchobanoglous et al. (2014)
Mixing	0.8424 kWh/$m^3_{reactor}$	Tchobanoglous et al. (2014)
Sludge dewatering (screw press)	0.0009 kWh/$m^3_{wastewater}$	Tchobanoglous et al. (2014)
Settling	0.00095 kWh/$m^3_{wastewater}$	Tchobanoglous et al. (2014)
SBR aeration	0.320 kWh/$m^3_{wastewater}$	Energy balance
Fermentation heating	14 kWh/m^3_{fed}	Energy balance
DOW grinding	0.00051 kWh/kg_{DOW}	Zeeman et al. (2008)
FWDs use	0.51 kWh/$m^3_{mixture}$	Evans et al. (2010)
Composting	9 kWh/t_{sludge}	Fisher (2006)