A procedure for evaluating the most environmentally sound alternative between two on-site small-scale wastewater treatment systems

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Abstract

The main aim of this study was to evaluate the most environmentally sound alternative between two on-site small-scale wastewater treatment systems (designed for 15 inhabitants), namely an activated sludge (AS) compact system and a constructed wetland (CW) system (both in linear LDPE), using Life Cycle Assessment (LCA). The procedure considered three sensitive parameters with three values. All the 27 combinations were evaluated with three different impact assessment methods (generating 81 comparison cases): IPCC 2007 100 years, Ecological Footprint and ReCiPe 2008 H. The CW system was the best environmental choice in 93% of the cases. The AS electricity consumption was the most influencing parameter. Realizing the two treatment systems in different European countries, the AS system would be the best environmental choice in some cases. Considering the production of electricity with photovoltaic systems, the total impact of the AS system, evaluated with the ReCiPe 2008 H method, would be smaller than that of the CW system. The variation of the operating lifetime parameter had a major influence on the CW system, where the greatest consumption of energy and resources occurs during the construction phase. There were significant differences among the results with ReCiPe 2008 H and those with Ecological Footprint and IPCC 2007 100 years. Therefore, in a LCA study, it would be preferable to adopt several impact assessment methods in order to verify how the results can vary.

Key words: activated sludge; constructed wetland; electricity; LCA; LLDPE; small-scale

1. Introduction

1.1. State of the art

In recent years, there has been an increase in environmental awareness in all technology fields, including the wastewater management sector. This has led to giving more and more importance to all the aspects related to the sustainability of the treatment systems. At the same time, it was necessary to adopt tools capable of assessing the sustainability of the processes.

Life Cycle Assessment (LCA) is one of the most used tools since it allows to evaluate the environmental performance of alternative treatment systems considering their entire life cycle (Curran, 2008). LCA allows to compare different systems considering the consumption of resources as well as the emission of pollutants that may occur during their entire life cycle, which may include the extraction of raw materials, the production and processing of materials, the transport, the phase of use and, finally, the end of life (ISO 14040, 2006; ISO 14044, 2006).

In recent years, there have been several studies on the application of LCA on different wastewater treatment technologies. In particular, Corominas et al. (2013) published a major research review on this subject.

It is worth noting that, with the progress of the research, the performed studies improved their reliability and complexity. LCA has proved to be a valuable tool capable of supporting the decisional processes in the context of a sustainable management of wastewater in order to avoid *problem shifting* (Larsen and Hauschild, 2008). Such phenomenon refers to the risk of acting only shifting environmental impacts from a life cycle phase to another or from an environmental compartment to another, without a holistic vision of the system (Curran, 2008).

However, there are still some limitations in the application of LCA to wastewater management. The subjectivity of the analysis is one of the unresolved problems. In fact, even respecting the ISO standard constraints, the application of LCA to wastewater treatment systems suffers for an excessive variability in terms of the definition of the functional unit and the system boundaries, due to the selection of the impacts assessment methodology and the procedures used for the interpretation of the results (Corominas et al., 2013).

Considering whether to study all the life cycle phases (construction, use and disposal) is a preliminary decision to take when defining the study system boundaries. Some authors only consider the use phase, since they assume that the impacts related to the other life cycle phases are negligible if compared with the impacts of the use phase.

However, for some treatment technologies, the contributions of the construction phase to the total impacts are significant, sometimes even higher than those of the use phase. Some examples are constructed wetlands, sand filtration and conventional treatments with the addition of microfiltration and ozonisation processes (Corominas et al., 2013).

In particular, comparing conventional treatments (e.g. activated sludge processes) with constructed wetlands for the treatment of wastewater produced by small communities, the importance of considering all the life cycle phases has been pointed out (Dixon et al., 2003; Machado et al., 2007; Yildirim and Topkaya, 2012; Lopsik, 2013; Di Muro et al., 2014).

The incidence of the construction phase on the total impacts depends on the size of the treatment plant, usually expressed as the maximum number of the population equivalent (PE) that the system is able to treat. Different authors have shown how the per capita environmental loads of the construction phase of wastewater treatment plants (WWTPs) are inversely proportional to the facility size (Lundin et al., 2000; Doka, 2009; Lorenzo-Toja et al., 2015; De Feo and Ferrara, 2016). Doka (2009) showed that increasing the size of WWTPs is more efficient even for the use of the sewers system.

The lack of high quality inventory data is another important issue (linked to the subjectivity of the analysis). It is a critical aspect for both the affordability and specificity of primary data as well as for the necessity to use data consistent with the geographic context of the LCA study (Köhler et al., 2012; Li et al., 2013; Lehtoranta et al., 2014; Zang et al., 2015). The need for site-specific data depends on the sensitivity of the territory in relation to the pollutants, energy production, transports and industrial and technological processes (Köhler et al., 2012; Li et al., 2013; Lehtoranta et al., 2014; Zang et al., 2015).

There is another important aspect to point out with reference to the WWTP size. In fact, there are many studies on the sustainability of large WWTPs, along with research on smaller plants, that are rarely considered, with a treatment capacity less of one thousand than PE. However, all over the world, there are sparsely populated regions, rural areas, or areas with many scattered users due to the geomorphological features of the territory (Lehtoranta et al., 2014).

The construction of sewer networks to connect the users to centralized plants is usually responsible for significant environmental impacts (Roux et al., 2011; Risch et al., 2015): this issue can be another reason in favour of decentralized solutions for the treatment of wastewater.

In situations similar to those described above, it is preferable to adopt on-site small-scale treatment systems (such as Imhoff tanks, constructed wetlands, compact activated sludge systems, etc.), for a PE less than one hundred. A single small-decentralized treatment system produces small environmental impacts, but many on-site small-scale systems can produce enormous burdens. Therefore, even for such treatment alternatives, it is desirable to evaluate the environmental impacts with a decisional process. For these reasons, it can be highly interesting to perform a LCA analysis to compare the alternative solutions of on-site small-scale treatment systems with a treatment capacity of a few PE.

The issue of the availability of high quality inventory data is even more relevant for this category of treatment system. Considering all the life cycle phases and, in particular, the use of site-specific data are important aspects to study in greater detail.

1.2. Objectives of the study

In the light of the considerations discussed in the previous section, this study tries to fill the cited gaps presenting the application of LCA to the comparison of two alternatives on-site small-scale treatment systems designed for 15 PE: an activated sludge (AS) compact system and a constructed wetland (CW) system.

The LCA study took into consideration 15 PE on the basis of an analysis of the Ecoinvent 2.0 database of the software tool SimaPro 7 with reference to the resources available for the modelling of the wastewater treatment. In the Ecoinvent 2.0 database, there are WWTP processes subdivided into five capacity classes on the basis of the PE number. The lowest class considers a capacity interval of 30-2,000 PE, while there is no information available for under 30 PE (De Feo and Ferrara, 2016). For these reasons, 15 PE was chosen as the mean value of the treatment interval not considered by the Ecoinvent 2.0 database.

The study considered both primary and site-specific data in order to answer the issue related to the poor availability of high quality data. Despite this, for those sensitive parameters lacking highly reliable data, an innovative procedure for the analysis of the model that took into consideration 81 cases of comparisons between the two treatment systems was adopted.

The adopted procedure considered three sensitive parameters. Moreover, three values were assumed for each parameter: a central value and other two values obtained subtracting and summing 33% to the central value. All the 27 possible combinations of the three parameters with the three values were considered.

Finally, in order to verify whether the choice of the impact assessment method could affect the results, three different methods (with different levels of complexity) were used: IPCC 2007 100 years (with one impact category, such as the global warming and with a time horizon of 100 years), Ecological Footprint (with three impact categories) and ReCiPe 2008 H (with 18 impact categories and 17 damage categories).

The main aim of this study was to evaluate the environmental performances of two different on-site small-scale treatment systems (for 15 PE) by means of the LCA methodology applied in order to choose the most environmentally sound alternatives among 81 comparisons (corresponding to 27 cases examined with three impact assessment methods). Therefore, the adopted procedure gave a new role to both the sensitivity analysis as well as the choice of the environmental impact assessment methods that were an integral part of the LCA procedure before the generation of the results.

The two compared small-decentralized treatment technologies were the compact AS system and the CW, designed for 15 PE.

In addition to the general aim of the study, which is the comparison between the two alternatives treatment system in order to choose the most environmentally sound solution, the influence of the operating lifetime was evaluated. Moreover, due to the high influence of the electricity consumption on the environmental performance of the AS system, the influences of using different energy sources were also examined.

2. Material and Methods

2.1. Treatment system design

The treated wastewater (effluent) was applied below the ground surface via drain tubes with a sub-irrigation system for both the compared systems. The untreated wastewater entering into the two systems (influent) had the same chemical-physical characteristics as well as the same flowrate (175 l/inhabitant/day). The two treatment systems were designed to assure concentrations in the effluent less than the Italian compliance limits for the discharge into the ground (Table 1).

Table 1

Requirements for the discharge of urban wastewater into the ground in Italy.

N.	Parameter	Unit of measure	Value
1	pH		6 – 8
2	SAR		10
3	Coarse materials	-	absent

4	Total suspended solids	mg/L	25
5	BOD_5	mg O_2/L	20
6	COD	mg O_2/L	100
7	Total Nitrogen	mg N/L	15
8	Ammonium Nitrogen	mg NH_4/L	5
9	Total Phosphorus	mg P/L	2
10	Total surfactants	mg/L	0,5
11	Aluminium	mg/L	1
12	Beryllium	mg/L	0.1
13	Arsenic	mg/L	0.05
14	Barium	mg/L	10
15	Boron	mg/L	0.5
16	Total chromium	mg/L	1
17	Chromium (VI)	mg/L	0.05
18	Iron	mg/L	2
19	Manganese	mg/L	0.2
20	Nickel	mg/L	0.2
21	Lead	mg/L	0.1
22	Copper	mg/L	0.1
23	Selenium	mg/L	0.002
24	Tin	mg/L	3
25	Vanadium	mg/L	0.1
26	Zinc	mg/L	0.5
27	Sulphides	mg H_2S/L	0.5
28	Sulphites	mg SO_3/L	0.5
28	Sulphates	mgSO_4/L	500
30	Active chromium	mg/L	0.2
31	Chlorides	mg Cl/L	100
32	Fluorides	mg F/L	1
33	Total phenols	mg/L	0.1
33	Total aldehydes	mg/L	0.5
35	Total aromatic organic compounds	mg/L	0.01
36	Total nitrogenous organic compounds	mg/L	0.01
37	Phosphorus pesticides	mg/L	0.01

The treatment systems had the components shown in Fig. 1. The AS system and the CW system differed only in the secondary treatment, while they had the following common units:

- Degreaser;
- Imhoff tank;
- Sub-irrigation system (composed of a discharge sump and drainage tubes).

The AS system is composed of the tank for the biological process (with an internal sedimentation cone as well as the diffuser plates), the connection to the air compressor, and the final sump for the effluent sampling (for the periodic compliance control of the chemical-physical parameters).

The CW system is composed of one derivation sump and three level sumps (upstream and downstream), and 23 trays distributed in three parallel lines. The derivation sump is also used as an effluent sampling sump.

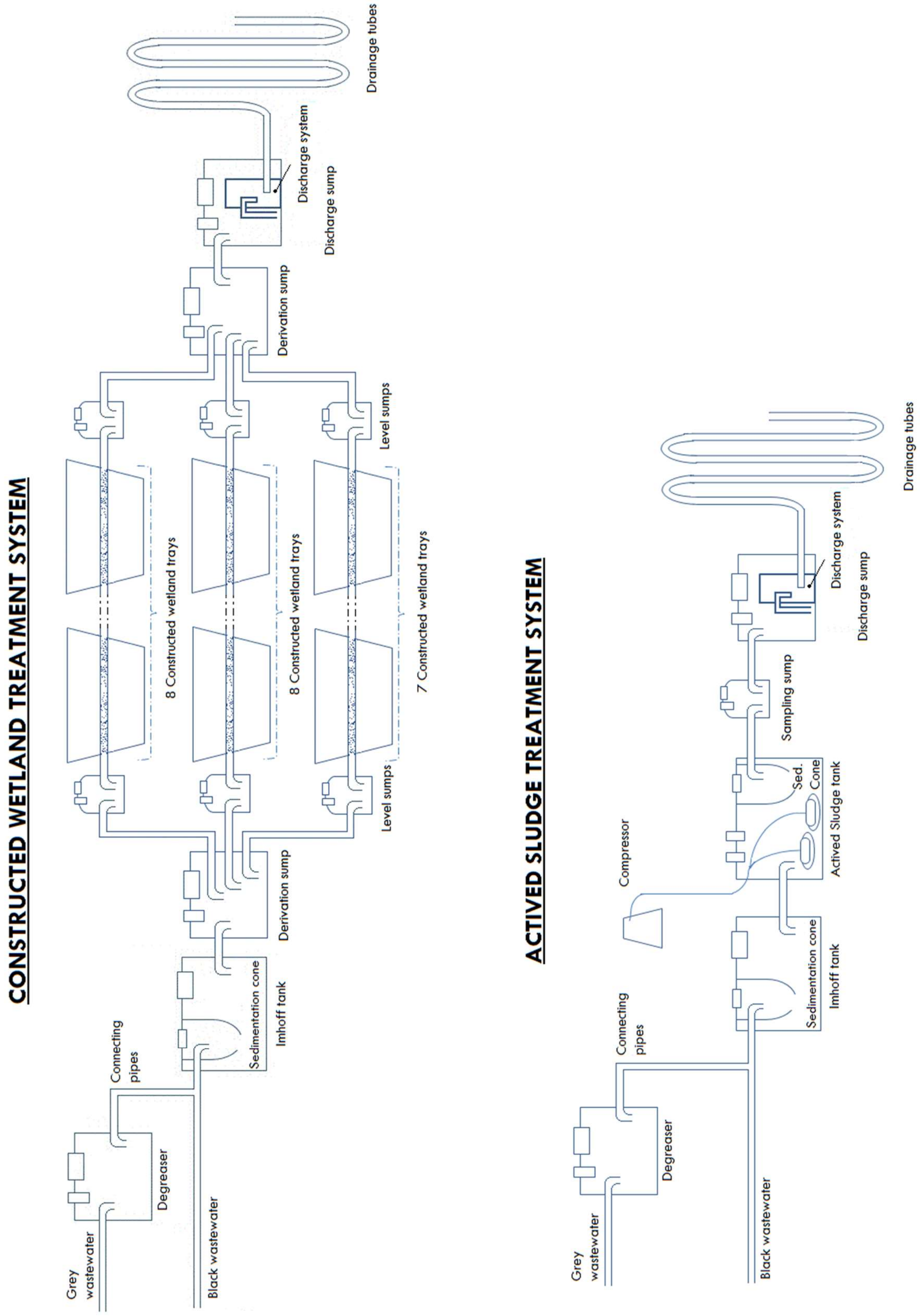

Fig. 1. Schematization of the two alternative on-site small-scale treatment systems.

2.2. Functional unit and system boundaries

Removing the pollutants load is the main function of a wastewater treatment system. There are two main definitions of the functional unit (i.e. the quantified performance of the system to use as a reference unit) in current literature. Firstly, the functional unit (f.u.) is defined on the basis of the wastewater volume (usually as m^3) (Foley et al., 2010; Pasqualino et al., 2011; Di Muro et al., 2014; Wang et al., 2015). Secondly, the f.u. is defined on the basis of the wastewater environmental load (usually as PE) (Tillman et al., 1998; Hospido et al., 2008; Remy and Jeckel, 2012; Fuchs et al., 2011; Lopsik, 2013; Risch et al., 2015).

This study considered a f.u. defined on the basis of the number of PE in order to compare two very different treatment alternatives (AS and CW) as well as to design the two systems with the same treatment capacity better.

Therefore, the f.u. adopted in this study was the treatment of wastewater produced by 15 PE in a variable time horizon of 10, 15 and 20 years.

All the phases of the treatment systems life cycle were included in the system boundaries: construction, use and disposal.

The construction phase considered the environmental loads related to the following aspects:

- production of the materials for the realization of all the system components;
- production processes of all the components;
- production processes of the auxiliary materials necessary for the facility management (e.g. the fill materials for the CW trays or for the excavation for the installation of the systems);
- excavations for the installation of the treatment facilities.

The soil excavated for the realization of the CW system was used as the filling material of the trays. In particular, it was assumed that the filling material was composed of a mixture of soil and gravel in a proportion 1:1. The hypothesis of using the excavated soil as part of the CW substrate is also present in other studies (Dixon et al., 2003). This is a rational choice since it avoids the production of impacts due to the transport of the excavated soil to a landfill.

The use phase considered the environmental loads related to the following aspects:

- consumption of energy for the functioning of the electric parts of the facilities;
- periodic replacement of materials and components useful for the functioning of the systems (e.g. the macrophytes and the filling material for the CW, or the chlorine tablets for the AS);
- disposal of the primary sludge produced in the Imhoff tank and the waste activated sludge;
- management and maintenance of all the facilities.

The disposal phase considered the environmental loads related to the disposal processes of all the components of the two treatment lines as well as the auxiliary materials. The landfill disposal was the assumed end of life.

The three life cycle phases took into consideration all the necessary transports. In particular, the following transports were considered:

- transport of the components from the manufacturing company to the site where the plants were hypothetically localized;
- transports for the periodic management and maintenance activities;
- transports of the intermediate disposal of sludge and other materials;
- transports for the final disposal of all the materials.

Fig. 2 proposes a schematization of the system boundaries.

Due to the relatively small size of the plants, it was possible to design the main components of the treatment systems with only one material. In particular, the study considered LLDPE (linear low-density polyethylene) tanks produced with the rotational moulding technique.

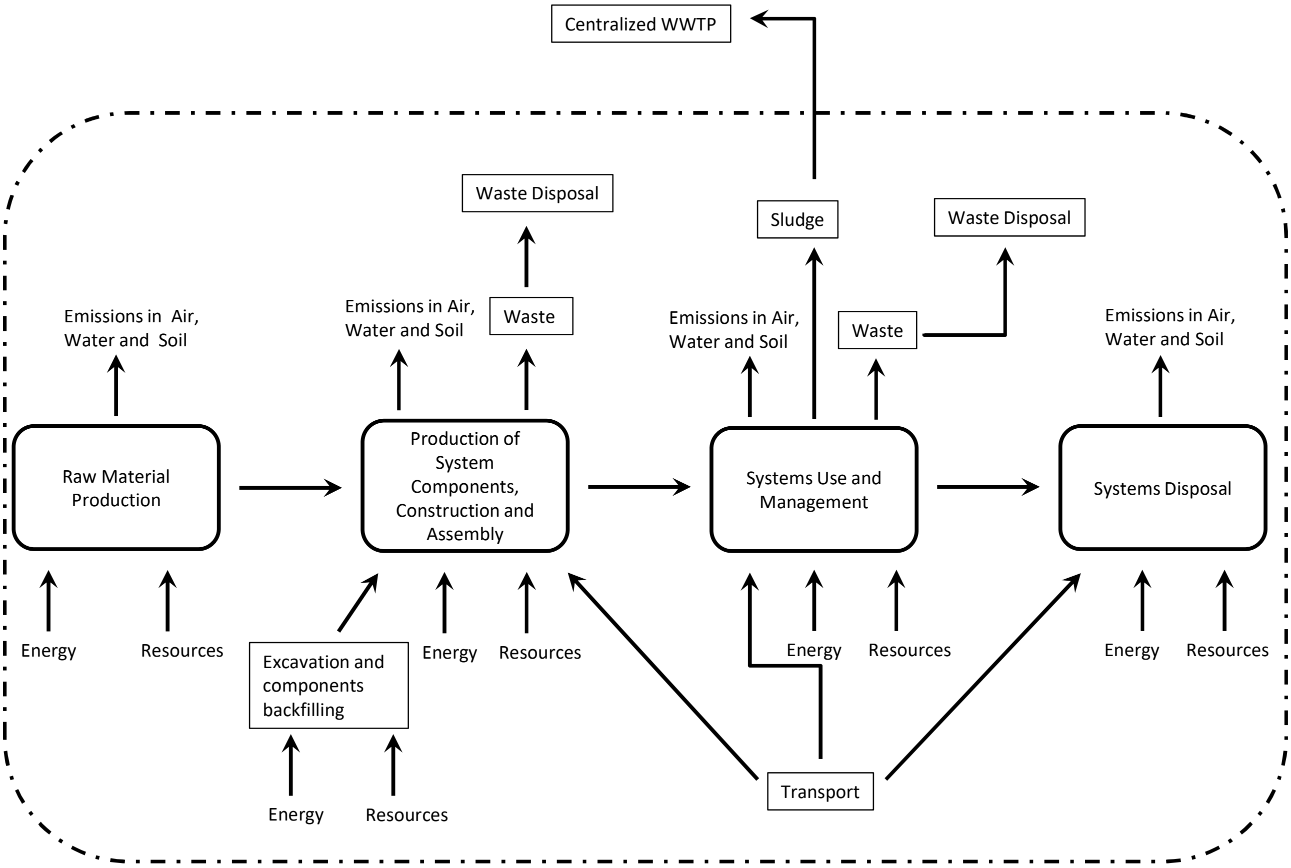

Fig. 2. Schematization of the system boundaries.

2.3. The procedure for the analysis of the model

After the realization of the modelling of the two wastewater treatment systems, the adopted procedure selected the possible "weak points" of the models, namely the parameters with the maximum uncertainty or, in other words, the most sensitive.

These parameters were: (1) the operating lifetime of the plants; (2) the electricity consumption for the aeration of the AS process; (3) the gas consumption in the rotational moulding process for the production of the LLDPE components.

The operating lifetime of the plants represents the time horizon considered in the model. This parameter could greatly influence the results, since the lifetime of the facilities affects the considered systems differently (Dixon et al., 2003; Larsen et al., 2010; Machado et al., 2007). In addition, it influences the contribution that the three life cycle phases gives to the total environmental load.

The consumption of electricity for the aeration is a key aspect in an AS treatment process since it gives a significant contribution to the total environmental load (Gallego et al., 2008; Hospido et al., 2008; Pasqualino et al., 2009; Yildirim and Topkaya, 2012). The uncertainty on the value to adopt for this parameter comes from the fact that the study considered a very small-scale treatment capacity (15 PE). There are very few data related to the electricity consumption of such a size. This parameter changes a lot with the size of the treatment plant (Lundin et al., 2000; Doka, 2009; Lorenzo-Toja et al., 2015), with it being fundamental to adopt site-specific data.

The gas consumption in the rotational moulding process for the production of the LLDPE components is the parameter with the highest impact of the entire process. The rotational moulding technique is present in both the treatment lines because all the components of the two systems were realized with such a system. However, the gas consumption has a greater influence on the CW treatment line because this system requires a bigger surface of LLDPE components compared with an AS treatment system with the same treatment efficacy.

These uncertainties were taken into consideration considering a 33% variation interval around the assumed value (central value) for all the three chosen sensitive parameters. As a direct consequence of this choice, there were three values for each sensitive parameter. Therefore, considering all the possible combinations of the three sensitive parameters with three possible values, 27 possible combinations came out (corresponding to 3^3). All the combinations were introduced into the two LCA models (one for the CW and one for the AS), in order to perform the comparison between the environmental performances of the two treatment systems. Therefore, the adopted procedure gave results for the 27 comparison cases taken into consideration.

Moreover, in order to avoid that the impacts assessment methods could significantly affect the results, three different methods were adopted: ReCiPe 2008 H, Ecological Footprint and IPPCC 2007 for a period of 100 years.

Therefore, the procedure took into consideration 81 comparisons between the CW and the AS systems, since the 27 cases were compared with three different impact assessment methods. It was assumed that the best environmentally sound solution would had been that winning in 60% or more of the cases (i.e. ≥ 49). On the contrary, the obtained results had to be considered not sufficient to establish what was the most environmentally sound alternative.

2.4. Inventory analysis

SimaPro 7.0 (PRè Consultans, Amersfoort, The Netherlands) was the software tool used to realize the LCA model of the treatment systems.

The technical catalogues of an Italian company producing small-scale treatment systems (in rotational moulding LLDPE) for municipal wastewater were the source for the primary inventory data both for the construction phase of all the system components as well as the excavation and backfilling techniques (Rototec technical catalogue, 2013).

The data related to the thickness of the tanks were the result of assumptions as well as mathematical extrapolations made on the basis of the technical drawings of the manufacturers (Rototec technical catalogue, 2013).

With reference to the inventory concerning the use phase of the treatment systems, the manufacturer technical manuals were the source of the primary data of all the operations related to the management and maintenance of the treatment facilities (Rototec technical manual, 2013).

Additional data required for the modelling (e.g. sludge production and electricity consumption) are reported in De Feo et al. (2016) and are the result of assumptions made after interviews with technicians, builders and operators of small-scale wastewater treatment plants operating in the Campania region of Southern Italy.

Tables 2 and 3 shows the primary inventory data of the main components of the treatment systems.

Table 2

Primary inventory data related to the construction phase of the main components of the modelled treatment systems.

Main components	Units	Weight (kg)	ϕ (dm)	h (dm)	Thickness (mm)	V (dm^3)
Degreaser	2	16.5	7.9	7.9	6	276
Imhoff tank	2	82	14.5	19.4	6	2642
CW trays	23	21	-	-	6	637
AS tank	1	82	14.5	19.4	6	2642
Sampling sump	1	2.56	4.3	4.7	6	-
Derivation sump	2	8.25	7.9	7.9	6	-
Level sump	6	9.9	5.8	7.9	6	-
Discharge sump	2	8.25	7.9	7.9	6	250
Sub-irrigation tubes system	2	78.5	-	-	-	-

Table 3

Primary inventory data related to the use phase of the main components of the modelled treatment systems.

Main components	Sludge	Maintenance Operations	
		Activity	Frequency
Degreaser	-	Degreaser control	Every 2 months
		Top waste and sludge removal; access and outlet pipes cleaning	Every 6 months
Imhoff Tank	50% volume of the Imhoff tank with 1 removal/year	Imhoff tank control	Every 6/12 months
		Sludge removal, inside walls and access-outlet pipes cleaning	Every 12 months
CW trays	-	Trays and level sump control	Every 3/4 months
		Sub-irrigation tubes cleaning	Every 12 months
		Macrophytes control and planting (if necessary)	Every 3/4 months
		Macrophytes pruning	Every 2/3 years
		Replacement of trays filling material	Every 4/5 years
AS tank	50% volume of the AS tank with 1 removal/year	AS tank control	Every 6/12 months
		Blower operation control	Every month
		Aspiration filter cleaning	Every 3 months
		Diffuser plates cleaning	Every 6/12 months
		Sludge removal, inside walls and access-outlet pipes cleaning	Every 12 months
		Table of chlorine replacement	Every 2 months
Sampling sump	-	-	-
Derivation sump	-	Control and sludge removal	Every 6 months
Level sump	-	Control and sludge residue removal	Every 3 months
Discharge sump	-	Control and sludge residue removal	Every 6/12 months
Sub-irrigation tubes system	-	Cleaning	Every 12 months

Table 4 contains all the values assumed for the sensitive parameters used for the construction of the two LCA models. Three values were considered for each parameter: a central value, a minimum value corresponding to 67% of the central value, and a maximum value corresponding to 133% of the central value.

The central value related to the gas consumption in the rotational moulding process (3 MJ/kg LLDPE) was assumed on the basis of information supplied by Italian companies dealing with the construction of rotational moulding machines (further details are available in De Feo et al., 2016).

The central value related to the electricity consumption for the AS aeration (20 kWh/PE/year) was provided by experts in the field (technicians and operators) operating in the Campania region of Southern Italy. The energy source was the Italian energy mix in the medium voltage deduced from the Ecoinvent 2 database (Table 5).

The three values assumed for the lifetime of the facilities (10, 15 and 20 years) are coherent with the literature data related to the lifetime of wastewater facilities (Emmerson et al., 1995; Dixon et al., 2003; Machado et al., 2007; Larsen et al., 2010; Yildirim e Topkaya, 2012; Lopsik, 2013).

Table 4

Values assumed for the sensitive parameters of the two LCA models (twenty-seven are all the possible comparison cases deriving from the combinations of all the values).

Range of variation	Lifetime	Electricity use for the AS aeration	Gas consumption in the rotational moulding process
Value (-33%)	10 years	13.33 kWh/PE/year	2 MJ/kg LLDPE
Central Value	15 years	20 kWh/PE/year	3 MJ/kg LLDPE
Value (+33%)	20 years	26.67 kWh/PE/year	4 MJ/kg LLDPE

The Campus of the University of Salerno, in the Campania region of Southern Italy, was the supposed location of the two treatment systems. The following are the distances considered for the transport phase: 500 km for the production site of the treatment systems materials and components (the distance takes into account where the manufacturer headquarters is effectively located related to the technical catalogue taken into consideration), 20 km for the sludge disposal, 10 km for the service centre, and 50 km for the disposal site.

Ecoinvent 2 system processes were the source of the background data, such as data relating to the Italian energy mix, the production of raw materials, the soil excavation and backfilling, the wastewater treatment plant for sludge disposal and the vehicles. In particular, Table 5 reports the Ecoinvent 2 system processes taken into consideration.

Table 5

Ecoinvent 2 system processes used for modelling the main treatment systems items.

Items	Ecoinvent 2 System Processes
Main LLDPE components	Polyethylene, LLDPE, granulate, at plant/RER S
Other small components	Polyvinylchloride, at regional storage/RER S
	Synthetic rubber, at plant/RER S
	Polypropylene, granulate, at plant/RER S
Rotational moulding	Electricity, medium voltage, production IT, at grid/IT S
	Heat, natural gas, at industrial furnace >100kW/RER S
Other moulding technics	Injection moulding/RER S
CW tanks backfilling	Gravel, unspecified, at mine/CH S
Excavation and backfilling	Excavation, hydraulic digger/RER S
	Waste (inert) to landfill S
	Sand, at mine/CH S
Chlorine tablets for wastewater disinfection	Sodium hypochlorite, 15% in H2O, at plant/RER S
Sludge	Waste water - untreated, EU-27 S
Transports in all life cycle phases	Transport, lorry 3,5-7,5t, EURO4/RER S
	Transport, passenger car, diesel, EURO4/CH S
	Transport, lorry >32t, EURO4/RER S
Electricity for AS aeration	Electricity, medium voltage, production IT, at grid/IT S
Disposal scenarios for treatment systems	Disposal, polypropylene, 15,9%water, to sanitary landfill/CH S
	Disposal, polyethylene, 0,4%water, to sanitary landfill/CH S
	Disposal, polyvinylchloride, 0,2%water, to sanitary landfill/CH S
	Disposal, plastics, mixture, 15,3%water, to sanitary landfill/CH S
	Waste (inert) to landfill S

2.5. Life cycle impact assessment

The environmental impacts of two treatment systems were evaluated with three different methods: ReCiPe 2008 H, Ecological Footprint and IPCC 2007 GWP 100 years. ReCiPe H and Ecological Footprint are multi-parametric methods; therefore, they provide an integrated vision that takes into account many environmental aspects in the calculation of the impacts.

ReCiPe 2008 H combines a midpoint problem-oriented level approach containing 18 impact categories with an endpoint damage-oriented approach containing 17 categories grouped into three macrocategories: damage to human health, damage to ecosystems and resource consumption. Damage to human health takes into consideration the following categories: climate change human health, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, ionising radiation. While, damage to ecosystems considers the following categories: climate change ecosystems, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation. Finally, resource consumption takes into consideration the following categories: metal depletion, fossil depletion. The hierarchist perspective (H) is based on the most common policy principles concerning the time frame and other issues (Goedkoop et al., 2013).

The Ecological footprint method calculates the amount of biologically productive land and water required by a population to produce the resources it consumes and to dispose of the waste generated by the consumption of fossil and nuclear fuel (PRé, 2015).

The IPCC 2007 GWP 100 years indicator is based on the factors of climate change over a period of 100 years considering the gaseous emissions of a potential greenhouse effect (PRé, 2015).

3. Results and discussion

3.1. Treatment systems comparison

The CW system was globally the most environmentally sound solution since it was the best solution in 75 comparisons out of 81 (i.e. 93%).

On the basis of the obtained results, the AS system produced environmental burdens significantly greater than the corresponding values obtained for the CW system. The energy consumption for the aeration was the parameter that influenced the environmental performance the most. In current literature, there are several studies pointing out the influence of the energy consumption on the sustainability of the AS system (Gallego et al., 2008; Hospido et al., 2008; Pasqualino et al., 2009).

It is important to analyse the percentage contribution that each phase of the life cycle (construction, use, and disposal) gave to the total environmental impacts (calculated with the three different methods considered) for both the treatment systems, as shown in Fig. 3. Table A1 (Supplementary materials) contains the data used to construct Fig. 3.

The construction was the most impactful phase for the CW system for all the impact assessment methods. The highest percentage influence of this phase was equal to 75% for ReCiPe 2008 H. This result was not surprising because the CW belongs to the extensive treatment systems that are characterized by a major consumption of energy and resources during their construction, while they usually have a more eco-friendly use phase (Dixon et al., 2003; Machado et al., 2007; Yildirim and Topkaya, 2012; Corominas et al.,2013; Lopsik, 2013).

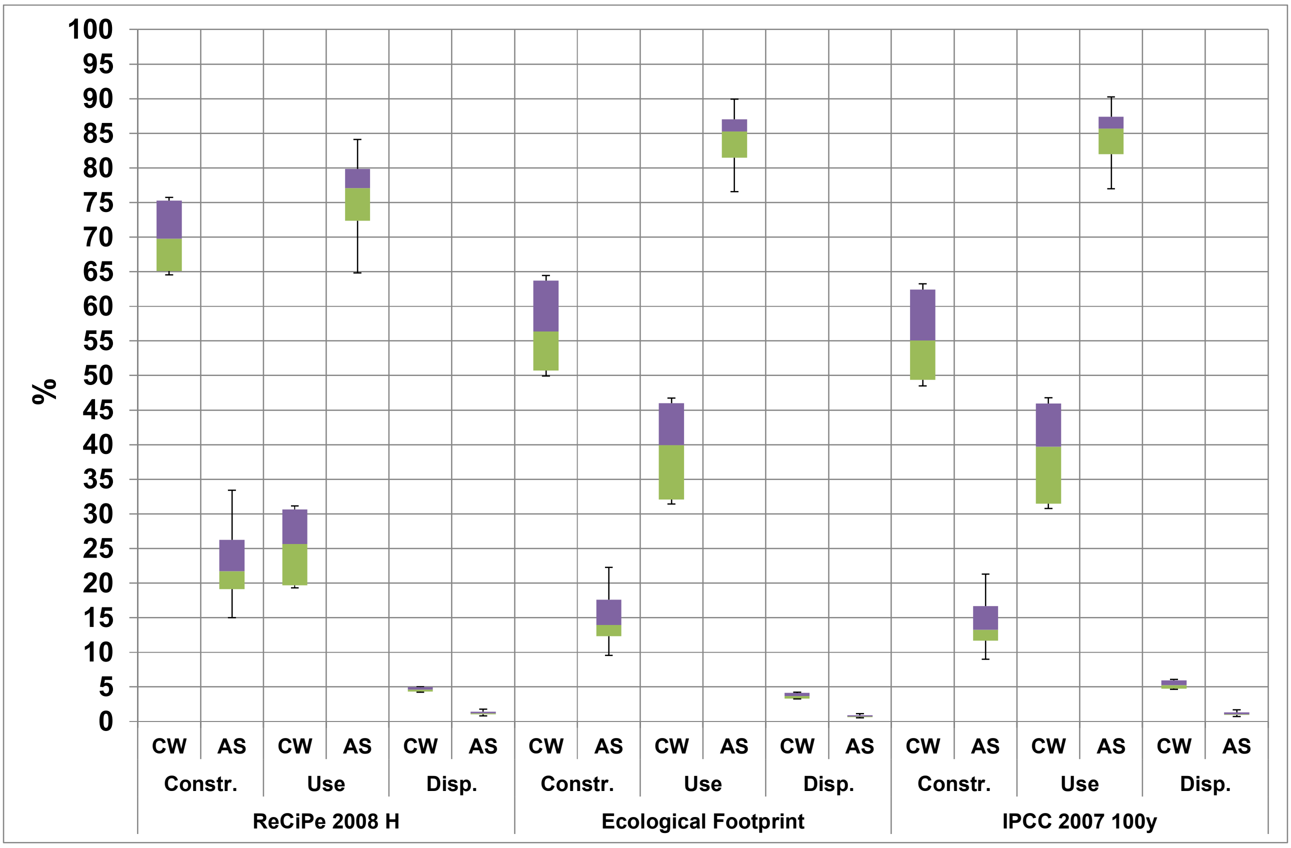

Fig. 3. Percentage contribution of each life cycle phase (Constr. = construction; Use; Disp. = disposal) to the total environmental impacts (calculated with ReCiPe 2008 H, Ecological Footprint and IPCC 2007 100 years) for the constructed wetland (CW) and activated sludge (AS) systems.

The construction phase for the CW system had environmental impacts always greater than the same phase of the AS system (Table A2 of Supplementary materials). The significant use of construction and auxiliary materials was the main contributor to the environmental impacts of the construction phase for the CW. In fact, the CW system requires greater surfaces than the AS to assure the same treatment capacity (Yildirim and Topkaya, 2012; Corominas et al., 2013). Therefore, there was a major need of construction materials for the realization of the CW system. In particular, since the two systems were mainly composed of LLPDE monoblocks, for the CW system there was a plastic consumption three times that of the AS system. Moreover, for the CW system there was a huge need of backfilling materials due to the major areas needed.

The filling material of the CW trays was composed of a mixture gravel-soil with the ratio 1:1. The use of gravel produced environmental impacts related to the transport from the producing company to the facilities site. With reference to the soil, the soil excavated for the underground installation of the facilities was reused, according to Dixon et al. (2003): this solution avoided producing additional burdens.

An opposite situation occurred for the use phase. In fact, for the AS system, the use phase provides a contribution to the total impacts always greater than 70% with all the methods adopted, reaching a peak of 90% for both IPCC 2007 and Ecological Footprint (Fig. 3). Moreover, the use phase of the AS system generated environmental impacts always significantly greater than the corresponding impacts for the CW system (Table A2 of Supplementary materials). As already mentioned, this was due to the huge electricity consumption necessary for the AS aeration that made the contribution of the other phases of the life cycle (i.e. construction and disposal) to the total impacts quite negligible.

The obtained results showed that the disposal phase of the treatment systems, usually, gave a negligible contribution to the total impacts (Fig. 3). Nevertheless, the percentage contribution of the disposal phase of the CW system was greater than the corresponding influence of the AS system (Table A1 of Supplementary materials). This was due to the construction of the CW facility requiring a quantity of plastic materials that was three times that of the AS system.

Fig. 3 shows that there was a major variability of the results obtained for the AS systems. In fact, only two of the three sensitive parameters influenced the design of the CW system: the operating lifetime and gas consumption in the rotational moulding process. While, the environmental performances of the AS system were (strongly) influenced by the electricity consumption for the aeration (which was the third sensitive parameter).

Fig. 3 shows that IPCC 2007 and Ecological Footprint gave very similar results. This was because both the methods mainly calculated the environmental impacts on the basis of the production of greenhouse gases. In fact, IPCC 2007 only considers the Global Warming impact category. With reference to the Ecological Footprint method, Fig. 4 points out that, the indirect consumption of soil due to the carbon dioxide disposal gave the main contribution to the total impacts for all the three life cycle phases as well as both the treatment systems.

Different results were obtained with the ReCiPe 2008 H method that takes into consideration a considerable number of environmental impacts for both the midpoint and endpoint levels. Therefore, the choice of the most useful and appropriate environmental impact assessment method, to use for an LCA study, has to be taken with great care.

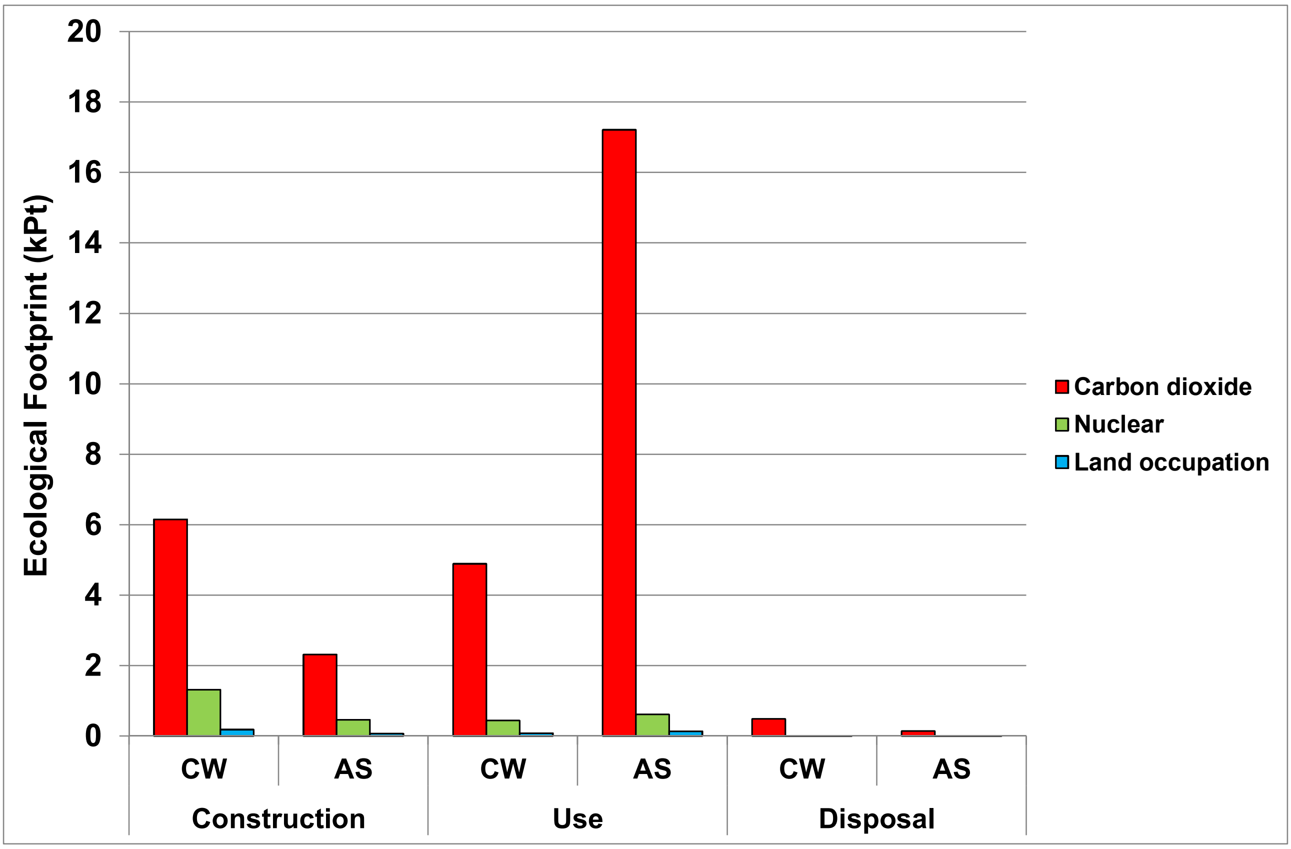

Fig. 4. Comparison among the contributions that the three impact categories of the Ecological Footprint gave to the total impact for the three phases of the life cycle for both the considered treatment systems (CW = constructed wetland; AS = activated sludge).

3.2. Evaluation of the operating lifetime influence

The influence of the operating lifetime of the facilities, estimated through the calculation of the annual environmental impacts, is another important aspect to consider. In fact, many studies focused on the relevance of the operating lifetime of the treatment systems on the environmental performances of the same facilities (Dixon et al., 2003; Corominas et al., 2013).

Fig. 5 shows how the total environmental impact of the two treatment systems, calculated with the three considered impact assessment methods, diminished increasing the operating lifetime from 10 to 15 years and then up to 20 years.

The obtained results show that the increasing of the operating lifetime of the facilities had a more significant effect on the CW system. This result has to be considered in the light of the fact that the annual environmental impacts of the use phase do not vary with the operating lifetime. On the contrary, the annual environmental impacts of both the construction and disposal phases diminishes with the lifetime. As previously discussed, the construction phase gave a very significant contribution to the total impacts for the CW system. On the contrary, the use phase was the most impactful for the AS system.

Another important aspect to points out is that while there was a significant environmental advantage when the lifetime increases from 10 to 15 years, the advantage was less considerable going from 15 to 20 years, for both the treatment systems as well as for all the three assessment methods. In fact, even if the absolute value of the environmental load of the use phase does not change upon increasing the operating lifetime, it will have an increasing percentage contribution on the total impact thus reducing the effect of the advantage due to the diminishing of the annual environmental impacts of the other two life cycle phases.

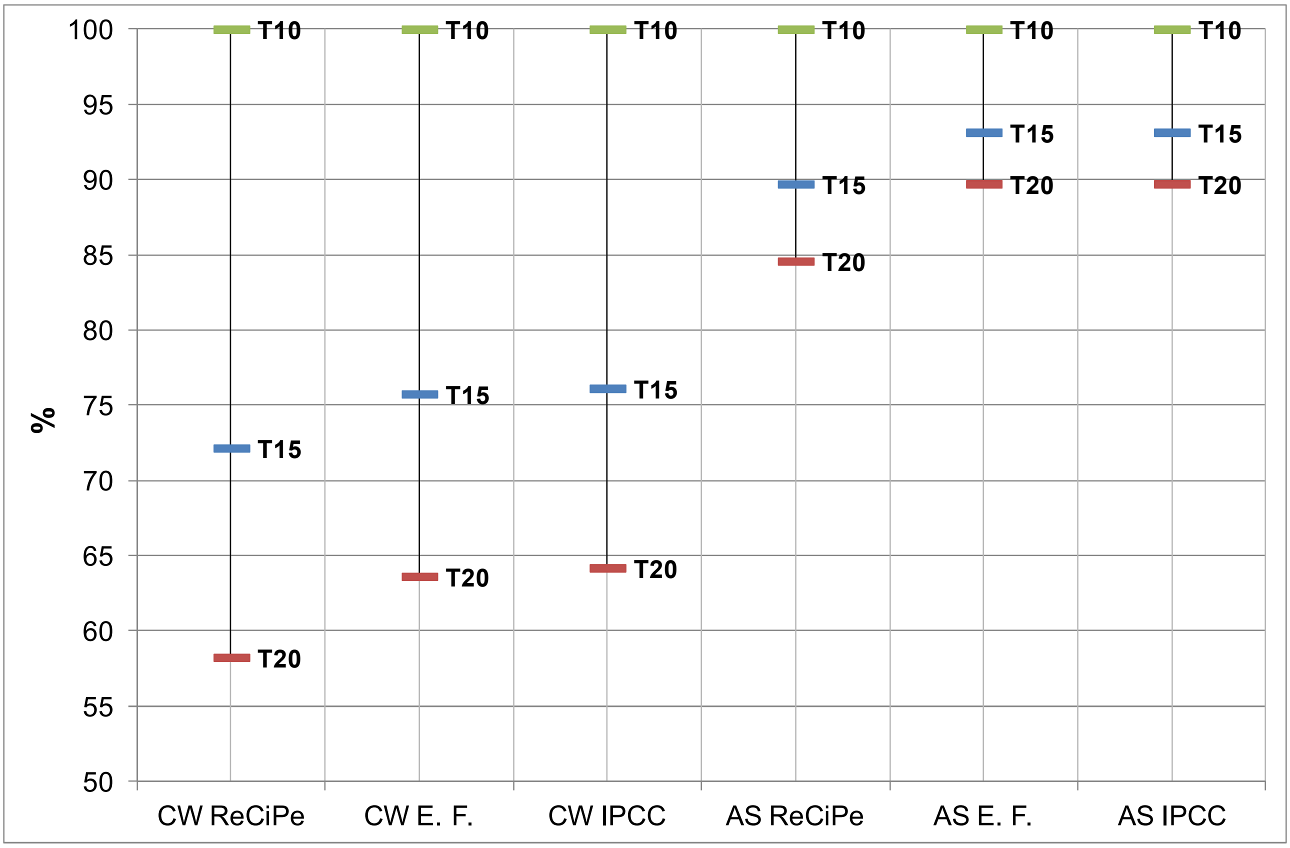

Fig. 5. Percentage diminishing of the annual environmental impacts with the increasing of the operating lifetime (10 – 15 – 20 years) for both the studied treatment systems (CW = constructed wetland; AS = activated sludge) and for the three considered environmental impact assessment methods (ReCiPe = ReCiPe 2008 H; E. F. = Ecological Footprint; IPCC = IPCC 2007 100 years).

Fig. 5 shows that very similar results were obtained for both the IPCC and Ecological Footprint methods, while the ReCiPe 2008 H method registered significant differences between the CW and AS systems. In particular, ReCiPe 2008 H emphasized the positive effect of increasing the operating lifetime. The differences in the results obtained with the three methods were due to the already discussed aspect about the central role assumed by the global warming in the IPCC and Ecological Footprint methods compared with ReCiPe 2008 H that, on the contrary, takes into account many other environmental aspects.

3.3. Evaluation of the environmental impacts assessment method influence

Three different environmental impact assessment methods (ReCiPe 2008 H, Ecological Footprint and IPCC 2007 100 years) were used inside the procedure useful to choose the most environmentally sound solution between the two on-site small-scale wastewater treatments alternatives considered. The three methods showed significant differences in the obtained results. The Ecological Footprint and IPCC 2007 methods agreed in considering the CW system the most environmentally sound in 100% of the 27 comparisons, while for the method ReCiPe 2008 H, this percentage dropped to 78%. Table 6 shows the comparisons among the environmental impacts calculated for the two alternative treatment systems with the three different assessment methods considered and for all the possible combinations of the three sensitive parameters (27 cases).

Table 6

Comparison among the environmental impacts calculated for the two alternative treatment systems (CW = constructed wetlands; AS = activated sludge) with the three different assessment methods considered: ReCiPe 2008 H (single endpoint), Ecological Footprint and IPCC 2007 100 years.

N.	Sensitive parameters			Environmental impacts					
	Time (T) years	Electricity AS (E) kWh/AE/year	Gas cons. (G) MJ/kg	ReCiPe 2008 H (single endpoint) Pt		Ecological Footprint (single point) kPt		IPCC 2007 100y kg CO_2 eq	
				CW	AS	CW	AS	CW	AS
1	10	13.33	2	514.79	453.10[a]	11.83	12.89	4165.57	4783.32
2	10	13.33	3	519.57	454.47[a]	11.95	12.92	4213.24	4797.01
3	10	13.33	4	524.35	455.84[a]	12.07	12.96	4260.91	4810.70
4	10	20	2	514.79	514.49[a]	11.83	14.57	4165.57	5434.06
5	10	20	3	519.57	515.86	11.95	14.61	4213.24	5447.75
6	10	20	4	524.35	517.24[a]	12.07	14.64	4260.91	5461.45
7	10	26.67	2	514.79	575.88	11.83	16.26	4165.57	6084.80
8	10	26.67	3	519.57	577.26	11.95	16.29	4213.24	6098.49
9	10	26.67	4	524.35	578.63	12.07	16.33	4260.91	6112.19
10	15	13.33	2	557.68	600.81	13.46	17.85	4763.91	6635.58
11	15	13.33	3	562.46	602.18	13.58	17.89	4811.58	6649.27
12	15	13.33	4	567.24	603.56	13.70	17.92	4859.26	6662.97
13	15	20	2	557.68	692.90	13.46	20.38	4763.91	7611.69
14	15	20	3	562.46	694.27	13.58	20.41	4811.58	7625.38
15	15	20	4	567.24	695.65	13.70	20.44	4859.26	7639.08

16	15	26.67	2	557.68	784.99	13.46	22.90	4763.91	8587.80
17	15	26.67	3	562.46	786.36	13.58	22.93	4811.58	8601.50
18	15	26.67	4	567.24	787.73	13.70	22.97	4859.26	8615.19
19	20	13.33	2	600.57	748.53	15.09	22.81	5362.25	8487.84
20	20	13.33	3	605.35	749.90	15.21	22.85	5409.93	8501.53
21	20	13.33	4	610.13	751.27	15.33	22.88	5457.60	8515.23
22	20	20	2	600.57	871.31	15.09	26.18	5362.25	9789.32
23	20	20	3	605.35	872.68	15.21	26.21	5409.93	9803.02
24	20	20	4	610.13	874.06	15.33	26.25	5457.60	9816.71
25	20	26.67	2	600.57	994.10	15.09	29.54	5362.25	11090.81
26	20	26.67	3	605.35	995.47	15.21	29.58	5409.93	11104.50
27	20	26.67	4	610.13	996.84	15.33	29.61	5457.60	11118.20

[a] combination where the environmental impact of the AS system was less than the corresponding value estimated for the AS system

The environmental impact of the AS system was less than the corresponding value estimated for the AS system only in 5 comparisons out of 81 (6.2%). This situation occurred only for an operating lifetime of 10 years and for the ReCiPe 2008 H method, with only one exception: 20 kWh/AE/year for the AS electricity consumption and 3 MJ/kg for the rotational moulding gas consumption.

The partially different results obtained with ReCiPe 2008 H depended, as previously discussed, on the fact that it considers many environmental aspects neglected by the other methods, Ecological Footprint and IPCC. In particular, fossil depletion was the impact category that influenced the results the most. As previously mentioned, the CW system needed a consumption of LLDPE material (660 kg) almost triple of the AS system (204 kg). In particular, the impacts generated by the production of a significant quantity of LLDPE penalized the environmental performance of the CW system in all those cases of comparison with a low-medium electricity consumption.

It is interesting to analyse the contribution of the three single endpoint macrocategories to the total impact evaluated with the ReCiPe 2008 H method.

As shown in Fig. 6, Resources was the damage macrocategory that gave the major contribution to all the life cycle phases as well as both the treatment systems.

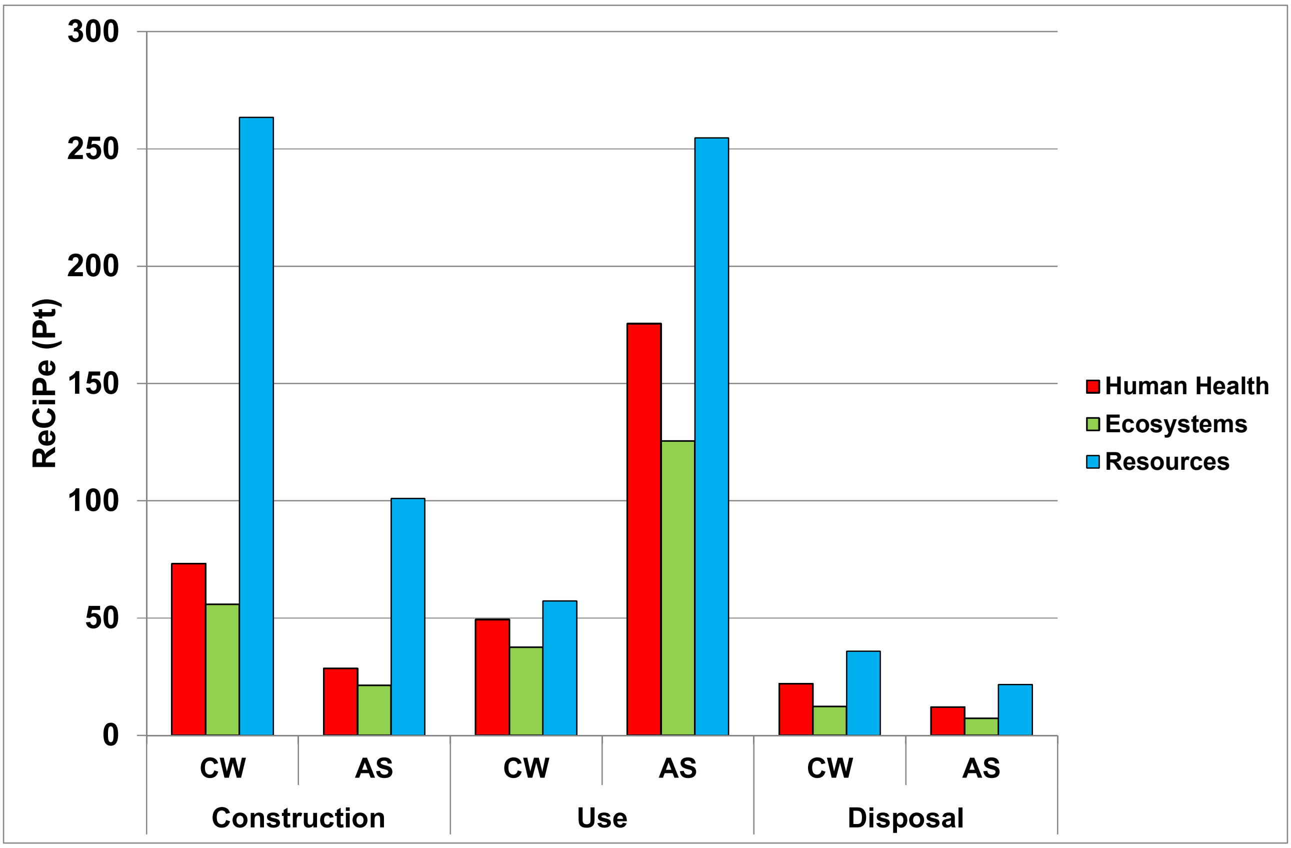

Fig. 6. Contribution of the three single endpoint macrocategories to the total impact evaluated with the ReCiPe 2008 H method for both the treatment systems (CW = constructed wetland; AS = activated sludge).

With reference to the construction phase of the systems, as already mentioned, these results were mainly due to the fossil depletion consequent to the production of the plastic materials needed for the construction of the treatment systems.

Even for the use phase of the AS system, Fossil depletion was the category that contributed the most on the Resources due to the electricity consumption that had a significant contribution on the damage macrocategory Human Health.

The disposal of the plastic materials was the most impactful phase for both the treatment systems with higher impacts for the CW as a consequence of the large amount of materials needed.

3.4. Influence of the energy source

Due to the high influence of the electricity consumption on the environmental performance of the AS system, the study evaluated the variation of the energy source.

The environmental impacts associated to the electricity consumption depend on the country energy mix considered. For this reason, the study considered the national energy mixes of different European countries such as Austria, Belgium, France, Great Britain, Netherlands, Spain and Switzerland. These countries were chosen on the basis of climatic reasons. In fact, it was decided to choose only countries with climate conditions useful for the implementation of CW systems with a satisfactory treatment efficacy. The data related to the energy mix of the considered European countries were taken from the Ecoinvent 2 database (Table 7).

Table 7

Ecoinvent 2 database system processes of the national energy mix of the European countries considered in the study.

Country Energy Mix	Ecoinvent System Processes
Netherland	Electricity, medium voltage, production NL, at grid/NL S
Italy	Electricity, medium voltage, production IT, at grid/IT S
United Kingdom	Electricity, medium voltage, production GB, at grid/GB S
Spain	Electricity, medium voltage, production ES, at grid/ES S
Belgium	Electricity, medium voltage, production BE, at grid/BE S
Austria	Electricity, medium voltage, production AT, at grid/AT S
France	Electricity, medium voltage, production FR, at grid/FR S
Switzerland	Electricity, medium voltage, production CH, at grid/CH S

Thus, the two alternative treatment systems were compared for each energy mix of Table 7 using the three impacts evaluation methods considered. Fig. 7 shows the obtained results in terms of the ratio between the environmental performance of the CW system and the corresponding performance of the AS system for the different energy mixes taken into consideration.

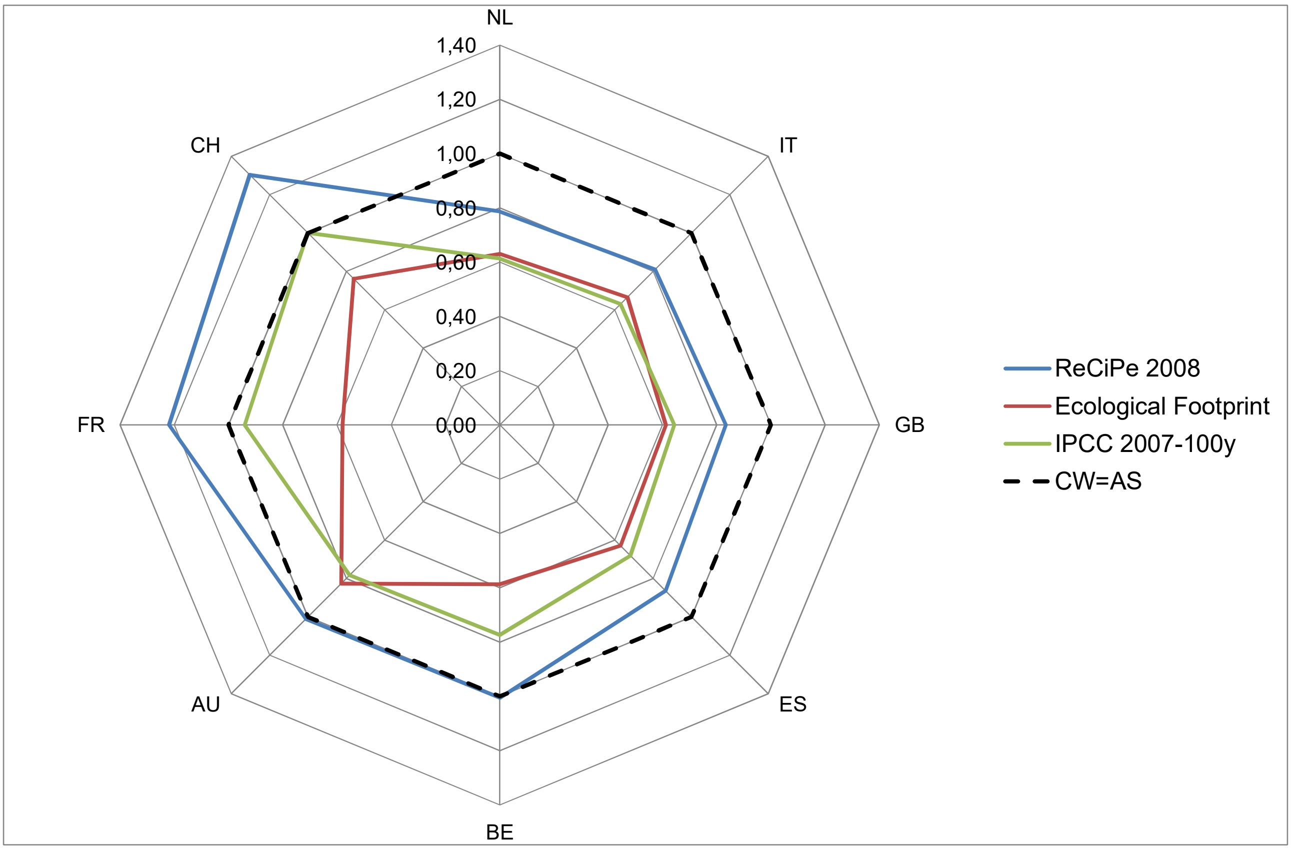

Fig. 7. Ratio between the environmental performance of the CW system and the corresponding performance of the AS system for different energy mixes (NL = Netherlands; IT = Italy; GB = Great Britain; ES = Spain; Be = Belgium; Au = Austria; Fr = France; CH = Switzerland) and for the three impact assessment methods (ReCiPe 2008 H, Ecological Footprint and IPCC 2007 100 years).

Where the ratio is greater than one, this means that the AS system is less impactful than the CW system. Obviously, it is the contrary when the ratio is less than one.

Fig. 7 clearly shows that the obtained results were different among the three impact assessment methods.

In terms of ReCiPe 2008 H, the AS system was the most environmentally sound treatment alternative with the French and Swiss energy mixes. While, the two alternative systems were quite similar with the Austrian and Belgian energy mixes. Finally, with all the other energy mixes, the CW system was the best solution from the environmental point of view.

Different results were obtained with IPCC 2007 and Ecological Footprint. In fact, with these methods, the CW system was the most environmentally sound solution with all the considered energy mixes. Only with the Swiss energy mix and with the method ICPP 2007, the environmental performance of the two alternative treatment systems were equivalent.

The differences in the results obtained with ReCiPe 2008 H and the other two methods depend on the peculiarities of each method. In particular, Global Warming has a dominant effect with IPCC and Ecological Footprint, especially with IPCC where it is the only environmental aspect considered, while with Ecological Footprint, it is one method out of three. Thus, the consumption of electricity is the most relevant factor independently from the energy mix considered. In fact, from Fig. 7 it is clear that, while the results obtained with ReCiPe 2008 H are different from those obtained with the other methods for each considered energy mix, with the other two methods the results were concordant for all the countries, excepted for France and Belgium. Those differences depended on the fact that Ecological Footprint is the only method considering the environmental impacts associated with the use of nuclear energy. In fact, as shown in Table 8, France, Switzerland and Belgium have a percentage composition of the energy mix where nuclear energy has a significant influence.

Table 8

Percentage composition of the national energy mix of the European countries taken into consideration in the study (Source: elaboration from Ecoinvent Reports - Ecoinvent v.2 - 05_EnergySystemSummary).

Country	Production technologies					
	Fossil	Nuclear	Hydro	Pumped storage	Renewable	Waste
Netherland	89.5	4.4	0.2	-	2	3.9
Italy[a]	78.7	0	18.4	-	2.3	0.3
United Kingdom	74.8	21.7	1.4	0.7	1.4	-
Spain[b]	55.2	27.6	14.1	-	-	-
Belgium	38.8	57.6	0.6	1.6	0.3	1.1
Austria	20.2	-	77.1	2.6	0.1	-
France	9	76.6	12.8	0.9	0.4	0.4
Switzerland	1.6	37.5	56.9	1.3	0	2.6

[a] The data related to the Italian energy mix were elaborated on the base of data retrieved from the website of the "IEA" International Energy Agency (http://www.iea.org/statistics/statisticssearch/report/?year=2000&country=ITALY&product=ElectricityandHeat)

[b] The data related to the Spanish energy mix were retrieved from the website of the Spanish Ministry of Industry (http://www.minetur.gob.es/energia/balances/Balances/LibrosEnergia/Energia_2001.pdf)

In the study, it was verified whether the use of a renewable energy source could influence the results. For this purpose, a process available in the Ecoinvent 2.0 database was used, related to the energy production with a photovoltaic system in Italy (*Electricity, low voltage {IT}electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel*).

Table 9 shows the results obtained with all the methods adopted for three comparison cases: Minimum case (with all the sensitive parameters at their minimum value), Medium case (with all the sensitive parameters at their central value) and Maximum case (with all the sensitive parameters at their maximum value).

Table 9

Comparison among the environmental impacts calculated for the two alternative treatment systems (CW = constructed wetlands; AS = activated sludge) with the three different assessment methods considered for the Minimum, Medium, and Maximum cases.

Methods	Minimum Case[a]		Medium Case[b]		Maximum Case[c]	
	CW	AS	CW	AS	CW	AS
ReCiPe 2008 H (Pt)	514.79	348.22	562.46	458.24	610.13	577.18
EF (kpt)	11.83	9.89	13.58	13.66	15.33	17.61
IPCC 2007 (kg CO_2 eq)	4165.57	3612.30	4811.58	4989.95	5457.60	6432.39

[a] Minimum Case (T10y-E13.33kWh/PE/y-G2MJ/kg)

[b] Medium Case (T15y-E20kWh/PE/y-G3MJ/kg)

c Maximum Case (T10y-E26.67kWh/PE/y-G4MJ/kg)

The obtained results pointed out that, using a renewable energy source for the electricity production, the AS environmental performance improved as well as the two systems became environmentally comparable. In current literature, other research has shown that using electricity from renewable sources would result in a significant improvement of the environmental performance of the wastewater treatment systems (Muñoz et al., 2008; Li et al., 2013; Opher and Friedler, 2016; Pintilie et al., 2016). Furthermore, with ReCiPe 2008 H, for all the comparison cases, the AS system was more eco-friendly. These results strengthen the consideration that the impact evaluation method can affect the results of the LCA study.

4. Conclusions

- The innovative procedure was able to choose the most environmentally sound solution. In fact, the obtained results showed that the CW system was the best environmental choice in 93% of the cases.
- The electricity consumption was the parameter that influenced the results the most because it is mainly responsible for the environmental impacts associated with the AS system.
- The environmental burdens associated with the electricity consumptions depend on the energetic source. In fact, realizing the two treatment systems in other European countries, the different energy mixes produced different results, with the AS system becoming the best environmental choice in some cases. Moreover, considering the production of electricity with photovoltaic systems, the total impact of the AS system, evaluated with the ReCiPe 2008 H method, was smaller than that of the CW system. Therefore, it would be appropriate to conduct LCA studies of industrial system focusing on the evaluation of the effects of the results using different energy sources since this could be the most significant environmental aspect.

- The operating lifetime of the facilities is another important aspect to consider. The variation of this parameter has a major influence on the extensive treatment systems such as the CW, where the greatest consumption of energy and resources occurs during the construction phase. In these cases, increasing the operating lifetime would imply a "dilution" of the total environmental impacts on a greater number of years. In this study, an increase of 33% of the operating lifetime produced a decrease of more than 25% of the total environmental impacts of the CW system.
- The analysis of all the results obtained using the three different impact assessment methods pointed out that there were significant differences among the results with ReCiPe 2008 H and those with Ecological Footprint and IPCC 2007 100 years. Those differences were due to the intrinsic features of the methods. In fact, ReCiPe 2008 H takes into consideration many environmental aspects, while the other two methods are not able to consider more comprehensively the complexity of the environmental mechanisms.
- Since the adoption of different impact assessment methods could produce significant differences in the results, it would be appropriate to define previously what methods to use in the LCA study, making a choice on the basis of the peculiarities of the study. Moreover, it would be preferable to adopt several methods in order to verify how the results of the study can vary.
- An interesting future development line of this research could be to extend the evaluation of the environmental performances of the CW and AS systems for the range 5-30 PE, considering intervals of 5 PE. This will allow to evaluate if the beneficial effect of the facilities scale factor (Lundin et al., 2000; Doka, 2009; Lorenzo-Toja et al., 2015) is also present for smaller on-site treatment plants as well as for different technologies as the CW systems.

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