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Life-cycle assessment of decentralized solutions for wastewater treatment in small communities

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ABSTRACT

This study benchmarks vermifiltration (VF) as secondary wastewater treatment in three natured-based decentralized treatment plants using life-cycle assessment. The comparison is justified by the comparatively easier and cheaper operation of VF when compared to more traditional technologies, including small rate infiltration (SRI), constructed wetlands (CW), and activated sludge (AS). Standard life cycle assessment was used and applied to three case-studies located in southern Europe. Material intensity during construction was highest for VF, but impacts during operation were lower, compensating those of the other phases. Impacts during the construction phase far outweigh those of operation and dismantling for facilities using constructed wetlands and activated sludge, when the number of served inhabitants is small, and due to lack of economies of scale. VF used as secondary treatment showed to contribute to reduce the environmental impacts, mainly in constructed wetlands and activated sludge. The replacement of CW by VF seems to bring important environmental benefits in most impact categories, in particular in the construction phase. The replacement by VF in facilities with SRI seems to result in the improvement of some of the impact categories, in particular in the operation phase. As for dismantling, no conclusive results were obtained.

Key words: activated sludge, constructed wetlands, LCA, slow rate filtration, vermifiltration

HIGHLIGHTS

- Vermifiltration is a promising technology.
- A LCIA is needed to better understand vermifiltration.
- The quantification of the environmental impacts will help researcher in future works.
- Constrution, operation and dismanteling phases are crutial to understand the life cycle in Wastewater Treatment Plants.
- LCIA is an important tool to study the environmental impacts of wastewater treatment.

1. INTRODUCTION

Wastewater treatment plants (WWTPs) are designed to reduce wastewater pollution and minimize negative impacts on human health and the environment (Zang *et al.* 2015). However, due to material, energy consumption, and emissions, WWTPs can cause environmental impacts (Capodaglio & Olsson 2019). Thus, the selection of a specific wastewater treatment technology should not be focused solely on technological insight, but should also integrate the human and environmental activities surrounding it, i.e., optimize the balance between technology and environment. A plethora of methods have been suggested to calculate the achievement of such a balance. The most frequent in wastewater technologies include decision support systems for designing sustainable technologies by (multi)objective optimization (Padrón-Páez *et al.* 2020); and aggregating indices, including (i) the use of set of (mainly local) indicators that incorporate environmental, societal, and economic sustainability (Cossio *et al.* 2020); (ii) life cycle impact assessment (LCA) (Myllyviita *et al.* 2016); (iii) energy analysis (Meneses-Jácome & Ruiz-Colorado 2020); (iv) socio-eco-efficiency analysis (Anwar *et al.* 2021); (v) a variety of footprints (Chen *et al.* 2020); and (vi) eco-efficiency (Dong *et al.* 2017).

Urban wastewater treatment for small rural communities, where technical and financial resources are usually limited, can pose a problem as solutions adopted in larger urban areas are not applicable (Capodaglio *et al.* 2017). Besides, the problem associated with the current treatment technologies is the difficulty in reaching sustainability (Bdour *et al.* 2009), assuming there is agreement about the measuring method. As for the latter, the largest consensus has been towards life cycle assessment, as shown by the more of two hundred LCAs made for wastewater treatment facilities over the last twenty years. Despite this wealth of experience, there is not yet agreement about many specificities of the method in the wastewater industry (Corominas *et al.* 2020), namely because the environmental impacts are strongly dependent on the geographical location, size, and installed unit operations, but also on socio-economic factors of the served population. The reproduction of methods and results from one place to another is therefore more difficult than in other industries. Given the diversity of possible combinations of natural and technological possibilities, the set of available LCA studies is still limited. It is, for instance, at the level of an emergent technology such as carbon capture, and inferior to the over three hundred made for a sub-category of the waste industry, such as waste-to-energy technologies (Mayer *et al.* 2019).

A number of small-scale treatment systems have been developed for small rural communities, which are adapted to the needs of these areas (Martin *et al.* 2006). These WWTPs have also good applicability in developing countries as they require less investment and have less technically demanding maintenance operations common in large centralized facilities (Muga & Mihelcic 2008). Given the need for alternative solutions, priority has been given to technologies which have minimum energy requirements, simple operational procedures, and sufficient level of inertia when faced large fluctuations in the flow and water quality (Salas 2004). Several types of decentralized wastewater treatment technologies for rural areas include: (i) active sludge system (AS) (Ahansazan *et al.* 2014), anaerobic sludge reactor (e.g. septic tank) (Tilley *et al.* 2014), stabilization ponds (Mara 2006), constructed wetlands (Vymazal 2011), infiltration systems (Li *et al.* 2015), and hybrid nature-based systems (Capodaglio *et al.* 2021).

Vermifiltration (VF) is an example of the latter, recognized as a low-cost and sustainable technology to treat wastewater (Jiang *et al.* 2016), sewage sludge (Zhao *et al.* 2010) and fecal matter (Furlong *et al.* 2016). On top of the above-mentioned advantages over conventional wastewater treatment solutions, VF has been shown to have higher efficiencies when flows are small (Li *et al.* 2008). It is a bio-oxidative process combining filtration with vermicomposting processes (Pathania *et al.* 2013) in vermifilters (VFs) (Tompkins *et al.* 2019). Filter packing in VFs is constituted by an organic packing and an inert packing (Lourenço & Nunes 2017a). It usually includes sawdust and vermicompost (Lourenço & Nunes 2017b), peat and wood flour (Li *et al.* 2009), wood chips, (Li *et al.* 2008) for organic packing; and gravel, quartz sand (Adugna *et al.* 2019), river bed gravel, mud balls, glass balls (Kumar *et al.* 2014), ceramsite and coal, for inert packing (Wang *et al.* 2010). Many of these packing materials are wastes from other activities, which are recycled into secondary raw materials, in line with circular economy principles. VF has found application in households, small communities, and to treat mixtures of urban and industrial wastewater (Sinha *et al.* 2014). It is also accepted that VF can be more cost-effective when compared with conventional WWTP (Liu *et al.* 2012) since it does not require mechanical equipment other than pumps (Sinha *et al.* 2008). Several VF are already working in France (1,000 PE) (RECYCLAQUA 2019), Spain, Chile (Fundación Chile 2019), Brazil (Madrid 2016), and P. R. China (Nie *et al.* 2013).

Like other WWTPs, small-scale treatment systems should be assessed carefully considering the inputs and outputs fluxes of the life cycle phases, evaluating its environmental performance as a whole system. The method begins with the life cycle inventory (LCI) which includes the study boundaries, resources (raw materials and energy), emissions (atmospheric, waterborne, and solid waste), and disposal practices. It consists of detailed tracking of all the flows in and out of the product system, including raw resources or materials, energy, water, and greenhouse gases (GHG), and substances. Conversion of inventory into impacts is made in the characterization phase (LCIA). Characterization factors are used to convert each LCI information into impact categories (Van den Bossche *et al.* 2006).

LCIA has been used to explore the sustainability of WWTPs (Ortiz *et al.* 2007) and to compare between alternative unit treatment processes (Wu *et al.* 2010), and alternative integrated wastewater management solutions (Palme *et al.* 2005), but mostly focusing in traditional technologies for large population sizes in urban environment. Small-scale WWTPs in small rural communities, which commonly serve population sizes below 2,000 person-equivalent (PE) or process influent flow rates below 200 m^3 day^{-1} (Lens *et al.* 2001) have received little attention.

This study benchmarks vermifiltration (VF) as secondary wastewater treatment in three natured-based decentralized treatment plants using life-cycle assessment. The comparison is justified by the comparatively easier and cheaper operation of VF when compared to more traditional technologies, including small rate infiltration (SRI), constructed wetlands (CW), and activated sludge (AS). VF is also cheaper and less technical, engineering-intensive to install and operate (Singh *et al.* 2019). The study uses the international standards for LCA (ISO 14040 2006) and focuses also in obtaining important data related with the different life cycle phases for the vermifiltration technology in an environmental sustainability perspective.

2. CASE-STUDIES

The present study focuses on WWTPs used for wastewater treatment in rural areas with communities up to 120 PE. Three real case-studies were chosen: (i) a slow rate filtration plant (SRI); (ii) a constructed wetland (CW); and (iii) an self-supporting activated sludge prefabricated steel unit (AS). The data from each WWTP necessary for the inventory and analysis of the current WWTPs were retrieved from published studies (Machado *et al.* 2007; Nogueira *et al.* 2009). To ease interpretation, the case-studies were named according to their original treatment systems. The systems were evaluated first by considering their present process diagram (base solution), and after a hypothetical replacement of the secondary treatment by vermifiltration (VF) (alternative solution).

SRI includes a pre-treatment followed by the slow infiltration system with *Populus euroamericana* and *Eucaliptus colmadulensis* as the used biomass, which occupies an area of 2,000 m^2. It has a design capacity of 40 PE in winter and 120 in summer, with a flow rate of 5.0 m^3 day^{-1} in winter and 15.0 m^3 day^{-1} in summer. The biomass produced is harvested each 5 years, shredded, and sold to the paper pulp industry. The irrigation system is formed by a polyethylene piping network. It is an experimental infrastructure located at Carrión de los Céspedes (Spain). CW is an experimental infrastructure located also in Carrión de los Céspedes (Spain). It includes an Imhoff tank which is used as primary treatment and two vertical-flow wetlands in series with 317.0 m^2 each, followed by a horizontal-flow wetland with 277.0 m^2. Grown biomass is cut yearly and transported to a landfill. It has a design capacity of 120 PE and processes a flow rate of 15.0 m^3 day^{-1}. AS is a full-scale municipal infrastructure located in Vila Verde (Braga, Portugal). It has a design capacity of 500 PE and treats a flow rate of 60.0 m^3 day^{-1}. It is constituted by an activated sludge tank with two surface aerators, working each 11 h day^{-1}, a primary clarifier and a secondary clarifier. It is assumed that all sludge produced in CW and AS is deposited in landfill for biogas production.

VFs are packed media filters using earthworms where wastewater is loaded intermittently into the upper surface and allowed to percolate through the system (USEPA 2002). Sizing is made according to the influent flow rate, hydraulic retention time (HRT), hydraulic loading rate (HLR), organic loading rate (OLR), packing depth, and abundance of earthworms (Singh *et al.* 2017).

The data necessary to compute the materials and resources necessary to build the VF was retrieved from literature, based on sizing optimization parameters (Lourenço & Nunes 2017a). The VF is made of pre-cast concrete and is constituted by an organic packing (sawdust) (0.3 m depth) and an inert packing (sand with 0.3 m depth and aggregate with 0.3 depth). The bottom of the VF includes a clarifier for wastewater recirculation.

3. METHOD

3.1. Life cycle inventory (LCI)

A full comparative life cycle inventory was carried out for the three WWTPs for the base solution and the alternative. A material balance was made for each individual process. In the analysis all the inputs required, and all the outputs generated were identified and quantified. The computations were made in OpenLCA® Nexus (version 1.7) (openLCA.org 2019), using Ecoinvent database, v. 3.5 (ECOINVENT 2019). CML Baseline v.4.4 (January 2015) was used to perform the quantification of the impacts, and EU25+3 (2000) for the normalization.

Though VFs are suited for primary or secondary treatment (Li *et al.* 2009), in order to keep the original primary treatments of the case-studies, VF was sized for secondary treatment only. SRI and AS included a septic tank, and CW an Imhoff tank (Figure 1), as primary treatments, which were maintained when studying the replacement of the original secondary treatment by VF. So, the LCIA is used to assess the impacts of using vermifiltration as secondary treatment, replacing wetlands and the activated sludge tank (Figure 1).

The sizing of the VF followed optimized operational parameters obtained before (Lourenço & Nunes 2017b), namely: (hydraulic retention time (HRT) (6 h), hydraulic loading rate (HLR) (0.89 m^3 m^{-2} day^{-1}), organic loading rate (OLR) (0.8 kg BOD m^{-3} day^{-1}), abundance of earthworms (20 g L^{-1}), recirculation flow rate (Q_r/Q_{mix}) (0.7) and the packing materials, which includes sawdust (0.3 m), quartz sand (0.3 m) and gravel (0.3 m), and wet to dry time ratio (W:D) (1:3) (Wang *et al.* 2014). The growth of earthworm's biomass was 0.12 g L^{-1} packing.day (Zhao *et al.* 2010). The size of the

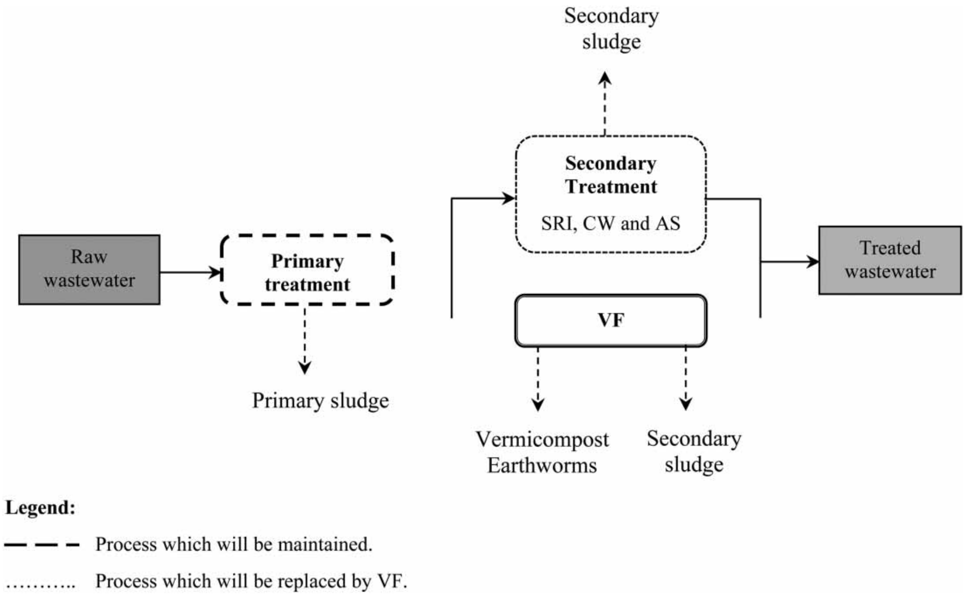

Figure 1 | Flowchart for SRI, CW and AS original WWTPs with VF alternative.

population of earthworms needed to be maintained constant throughout the exploration period, leading to the need to subtract some individuals. These are assumed to be released back in nature. Since both SRI-VF and CW-VF receive the same wastewater inflow (15 m^3 day^{-1}) (Table 1), and in order to keep the same W:D ratio in the VF (Wang *et al.* 2014) we assumed the same pumping work time and thus, the same electricity consumption.

Since the lifetime of a typical WWTP is between 25 and 50 years (Piao *et al.* 2016) the expected lifetime for the mechanical equipment was set at 15 years, and at 30 years for construction works.

The principles and requirements for LCI follow the established in the ISO 14000 series standards, namely for goal and scope (ISO 14040 2006), and inventory analysis (ISO 14044 2006). According to the standards, the functional unit (FU) may be one cubic meter (Piao *et al.* 2016), or one person equivalent (PE) Kärrman & Jönsson (2001)). In the present study, the functional unit is one PE.

The system boundary was established at the WWTP fence, with a gate to gate approach, which includes the analysis from reception of the ready to use raw materials and influent watewater to the outflow of treated wastewater and wastes. It is a common procedure when unit process are specifically studied. It was assumed that the sludges from the primary treatment are deposited in landfill. This assumption is intended to close the boundary for simulation purposes.

Construction, operation, and dismantling phases were included, following common procedures (Bravo & Ferrer 2011; Buyukkamaci 2013; Li *et al.* 2013). The LCI included detailed tracking of all inputs and outputs throughout the facilities' life cycle (construction, operation, dismantling), including assessment of raw resources or materials, water, energy and fuel, solid wastes, air and water emissions. The analysis involved several individual unit processes, being the inputs and outputs assigned to each of them. All the energy requirements for the processes identified in the LCI were first quantified in terms of fuel and electricity units. The fuel used to transport raw materials to each process is included as a part of the LCI energy requirements. Emissions are categorized as atmospheric emissions, water pollutants, and solid wastes. Atmospheric emissions (as greenhouse emissions) include carbon dioxide, methane and nitrogen oxide, and carbon dioxide equivalent, all reported as kg PE^{-1}. Water pollutants are reported as kg of pollutant per volume of wastewater per PE, which includes biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS). The volume of wastewater produced per PE was considered equal to 90 L (Paixão 2004).

3.1.1. Construction

The input flows considered in the construction phase included (i) fossil fuel (kg); (ii) construction materials (kg) and (iii) transport of materials (km). All values are reported as per functional unit. Design data for the different treatment schemes is shown in Table 1.

Table 1 | Detailed construction data and operation for the WWTPs

	Reference solution			Alternative solution		
Parameter	**SRI**	**CW**	**AS**	**SRI-VF**	**CW-VF**	**AS-VF**
Construction						
Unit operation area (m^2)[a]	2,000.0	594.0	95.0	12.5	12.5	50.0
Total plant area (m^2)[b]	2,014.8	620.7	139.4	27.3	39.2	94.4
Flow rate (m^3 day^{-1})	15.0	15.0	60.0	15.0	15.0	60.0
Population served (No.)	120.0	120.0	500.0	120.0	120.0	500.0
Wet to dry time ratio (W:D)[b]	–	–	–	1:3	1:3	1:3
Organic load (kg BOD PE^{-1} $year^{-1}$)	25.0	25.0	15.0	25.0	25.0	15.0
Earthwork volume (m^3)[c]	–	–	–	0.270	0.270	0.110
Total distance travelled (km PE^{-1})[d]	137.7	137.7	26.0	137.7	137.7	26.0
Operation*						
BOD load (kg)[e]	740.0	740.0	453.0	740.0	740.0	453.0
COD load (kg)	1,272	1,272	1,005	1,272	1,272	1,005
Pollutants removal (kg BOD)	666.4	629.4	397.2	654.6	654.6	400.5
Pollutants removal (kg COD)	1,081.1	1,017.5	828.5	960.6	960.6	758.8
Primary sludge production (kg)[f]	–	1,080.0	1,080.0	1,080.0	1,080.0	1,080.0
Secondary sludge production (kg)[g]	–	–	–	67–413	67–413	53–326
Total distance travelled (km)[h]	0.483	0.483	0.115	0.525	0.525	0.151

*Data for the 30 years of project.
[a]Exclusively for secondary treatment.
[b]Sum of primary and secondary treatment areas. 6 h wet time/18 hour dry time (Wang *et al.* 2014).
[c]Data not available for the reference situation.
[d]Transportation includes the way back, excluding the inputs which were not used for each particular WWTP.
[e]The organic load discharged to the receiver.
[f]Based on a daily production of 0.11 L $PE^{-1}day^{-1}$ (Paixão 2005) and a bulk density of 900 kg m^{-3} (Lourenço 2014). According to Machado *et al.* (2007) SRI did not produce primary sludge.
[g]We opted for recirculation of this material in VFs. Based on a production of 0.07 to 0.43 kg suspended solids kg^{-1} COD removed (Xing *et al.* 2011). Production in the reference solution was not reported.
[h]Distance to landfill, including the way back, plus the distance travelled for sawdust transport. The reference solution does not include the sawdust transport, which was 0.042 km PE^{-1} in SRI-VF and in CW-VF, and 0.036 km PE^{-1} in AS-VF.

Fossil fuel consumption was associated to (i) excavator (150–153 HP), wheel loader (260–285 HP), truck (413–496 HP), bulldozer (354 HP), and a diesel powered electricity generator (80 HP) (DSS 2019); and (ii) estimated travel distances.

The time of use of on-site and electric machinery was determined considering the unit operation area required to build the infrastructures, considering they were made from precast concrete. The latter was supplied by a local company 25 km away from the WWTPs. The sewerage system was built using PVC pipes.

Fuel consumption included diesel from fuel-powered electricity generators and transport vehicles. Fuel consumptions for the generator were based on the average values indicated by Klanfar *et al.* (2016). For road vehicles, heavy-duty transport vehicles (16–32 ton) in Portugal, Spain, Germany, and Luxembourg were assumed to be compliant with EURO 0–4 mix, 22 t total weight, 17.3 t max payload. Travelled distances are shown in Table 1.

3.1.2. Operation

During operation, four main activities were considered (i) wastewater treatment; (ii) sludge management; (iii) packing renewal, in the case of vermifiltration; and iv) substitution of equipment and parts. The wastewater treatment included the total volume of influent and effluent wastewater (m^3), therefore, assuming no losses in the process. The following flows were included: (i) electricity for pumping (MJ), (ii) fossil fuel consumption (kg).

Sludge treatment included the physic-chemical primary treatment and the biological secondary treatment. The following production values were assumed: (i) 0.11 L PE^{-1} day^{-1} for primary sludge (Paixão 2005) with 80% moisture; and

(ii) 0.070 kg suspended solids, from secondary sludge produced from vermifiltration (Xing *et al.* 2011). The percentage of nitrogen and phosphorous in the sludges were 0.45% and 0.30%. wet weight, respectively (Lourenço 2014). In larger WWTPs, polyaluminum chloride and aluminum sulfate are usually used as the inorganic flocculants in sludge thickening and dewatering (Piao *et al.* 2016), but due to the small size of the studied WWTP, they are not used. For VF, the secondary sludge is a mixture of earthworm castings and excess sludge (Xing *et al.* 2011). Due to the low production of secondary sludge in VF, it was assumed that all secondary sludge is recirculated.

It was assumed that the size of the population of earthworms in the VF increased for the first 200 days of operation, stabilizing after that at a relatively constant size for the remaining 30 years of project (Domínguez 2018). The production of earthworm castings, the precursor of vermicompost in the VF, followed a kinetic production of 11.9 mg g^{-1} earthworm biomass day^{-1} (Zhao *et al.* 2010).

The electricity for the operation phase was obtained from the grid, using the electricity mix of the country, AC, 1–60 kV. During this phase, the only relevant electrical equipment were a wastewater pump with 1.3 HP which worked for 6 h day^{-1}, and a recirculation pump with 0.07 HP which worked for 2 h day^{-1} in order to keep the adequate HRT (Bhunia *et al.* 2019) and an adequate wet to dry ratio in the VF (Wang *et al.* 2014) described previously.

The removal of the vermicompost from the uppermost layer of the VF was made every 3 months and assumed to be made using appropriate manual tools and was assumed to be used onsite to fertilize the green areas.

For sawdust, one single trip was assumed every year for each WWTP. The transport of primary sludge, secondary sludge and greases was assumed to be made at the same time, on a yearly basis in SRI-VF and CW-VF and, due to the amounts of primary sludge produced, twice a year on AS-VF. Therefore, the two flows were considered together. Transport of materials and wastes in and out of the facilities was assumed to be made by a 7.5 ton lorry, 3.3 t max payload, EURO 0–4 mix. The distance from the WWTPs to the landfill was 29.0 km (from Carrión de los Céspedes to Seville, Spain) (SRI-VF and CW-VF), and 14.4 km (from Vila Verde to Ferreiros – Braga, Portugal) (AS-VF). Other detailed information is shown in Table 1.

3.1.3. Dismantling

The flows in the dismantling phase included (i) fossil fuels consumption for the on-site machinery, electricity generator, concrete crushing machine and transportation (kg), and (ii) construction and general wastes (kg).

Fossil fuel consumption was related with excavator (150–153 HP), wheel loader (260–285 HP), truck (413–496 HP), and bulldozer (354 HP) and stone crushing machine (50 HP) with a mean fuel consumption of 32 L h^{-1} (Klanfar *et al.* 2016). A pneumatic hammer with 3.35 HP was fed by a diesel-powered electricity generator with 80 HP and a fuel consumption of 18 L $hour^{-1}$ at full load (DSS 2019). All the fuel consumptions were based on the same average values described above.

About 50% of the construction and demolition wastes were assumed to be crushed and recycled, following international experience (Trevor & Vallero 2019). Thus, detailed dismantling data does not include as wastes the materials that are recovered for reuse or recycling, which includes 50% of the total of concrete, gravel, sand, steel, and all the metal parts of the pumps. The remaining general wastes, which include steel mesh, PVC and HDPE pipes and PP, were considered to be 50% recycled. Transport of wastes out of the facilities was assumed to be made in the same conditions described in construction phase.

3.2. Life cycle impact assessment (LCIA)

The impact assessment step was made using the CML Baseline (v. 4.4, January 2005) characterization method, since it is one of the few which considers organic matter and nutrients as emissions. Normalization was made using EU25+3 (2000). No allocation was made. The selection of impacts was based on the works made by Corominas *et al.* (2013) and Jeppsson & Hellström (2002): Abiotic deplection (AD) (kg Sb eq.), Acidification (AC) (kg SO_2 eq.), Eutrophication (EUT) (kg PO_4^{3-} eq.); Fresh water aquatic ecotoxicity (FWT) (kg 1,4-DB eq.); Global warming potential (GWP) (kg CO_2 eq.); MAEC (Marine aquatic ecotoxicity) (kg 1,4-DB eq.); Ozone layer deplection (OLD) (kg CFC-11 eq.); Human toxicity (HT) (g 1,4-DB eq.); Photochemical oxidation (PO) (kg C_2H_4 eq.); and Terrestrial ecotoxicity (TE) (1,4-DB eq.).

4. RESULTS AND DISCUSSION

4.1. LCI

Table 4 shows the most important inputs for the three WWTP scenarios under study. The area of land occupied by the alternative VF solution is much lower than in the base solution, decreasing from 16.7 to 0.230 m^2 PE^{-1} in SRI-VF; and from 4.95 to

0.330 m^2 PE^{-1} in CW-VF. Given that the size of the activated sludge tank is similar to the vermifilter, the occupied land is equal, 0.190 m^2 PE^{-1}. Despite having the same served population (120 PE), SRI-VF occupies less land area than CW-VF due to different primary treatment systems, septic tank in SRI-VF and Imhoff tank in CW-VF. Imhoff tanks are used by small communities and their underground construction minimizes land use (Tilley *et al.* 2014). The estimated values are close to those obtained elsewhere for VF-based solutions. In France (Combaillaux), the typical area of land for a VF was 0.25 m^2 PE^{-1} (with no pre-treatment included) (RECYCLAGUA 2019). In rural areas of China, Nie *et al.* (2013) found that the typical area of land for VF varied from 0.060 to 0.21 m^2 PE^{-1} (with no pre-treatment included). In India, typical land area was reported to vary between 0.5 and 0.6 m^2 PE^{-1} (Sinha *et al.* 2014).

The amount of materials used during construction phase of the alternative were, by decreasing order, concrete (515.2 kg PE^{-1} in CW-VF), sand (46.9 kg PE^{-1} both in SRI-VF and CW-VF), gravel (44.7 kg PE^{-1} both in SRI-VF and CW-VF), and steel (18.2 kg PE^{-1} in CW-VF). These are somewhat higher than those found elsewhere for similar infrastructures (Sapkota 2016), namely for cement (8.98–21.1 kg PE^{-1}), sand (18.27–27.46 kg PE^{-1}), aggregate (28.58–73.71 kg PE^{-1}), steel (1.23–3.13 kg PE^{-1}), and PVC (0.006–0.31 kg PE^{-1}). Concrete use was always higher in the alternative solution due to the need to build the vermifilter (Table 4). Gravel represents one of the most significant inputs during construction of CW, resulting in being one the materials with the highest variations between the base and alternative solutions. In the opposite direction go sand and iron, both used in the construction of the vermifilter (Table 4).

Steel, stainless steel, and pumps came from suppliers far away from the construction sites, justifying the large transport distances (stainless steel, 5.50 km PE^{-1} for both SRI/SRI-VF and CW/CW-VF, and 1.20 km PE^{-1} for AS/AS-VF; pumps, 6.33 km PE^{-1} for both SRI/SRI-VF and CW/CW-VF, and 1.40 km PE^{-1} for AS/AS-VF).

Fossil fuel consumption is proportional to travelled distances, and the number of hours of electricity generator use in the construction and demolition phases. Steel and stainless steel transportation showed the highest fossil fuel consumption since these materials have the longest distance travelled between each manufacturer and the construction site (Table 2). In terms of fuel consumption, no significant alteration between the reference solution and the alternative was found due to the negligible contribution of the transport of sawdust for filling of the vermifilters.

The inventory during operation for the three WWTP is reported in Table 3. Discussion is henceforward referred to a period of 30 years. Both SRI and CW treat the same total inflow of 1,369 m^3 PE^{-1} while AS treats 1,314 m^3 PE^{-1}. Water consumption in the reference solution was of 142.7 kg PE^{-1} in SRI and CW to 1,629 kg PE^{-1} in AS-VF and, in the alternative of 142.8 kg PE^{-1} both in SRI-VF and CW-VF to 965.5 kg PE^{-1} in AS-VF. The amount of sawdust used during operation was 74.3 kg PE^{-1} for both SRI-VF and CW-VF, and 71.3 kg PE^{-1} for AS-VF. No sawdust or earthworms were used or vermicompost produced in the reference solution since they are specific to the filter packing of VF.

Table 2 | Estimated travel distances for transportation of inputs used in the construction of the WWTPs (per PE)

	Distance to WWTP (km)		
Input[a]	**SRI-VF**	**CW-VF**	**AS-VF**
Pre-cast concrete	0.42	0.42	0.10
Gravel	9.7	9.7	0.01
Quartz sand	10.5	10.5	1.20
Steel (inc. stainless steel)	36.3	36.3	8.00
Geotextile fiber (PP)	10.6	10.6	4.20
Pipes (PVC)	19.2	19.2	0.500
Pipes (HDPE)	11.5	11.5	0.400
Sawdust	0.040	0.040	0.020
Earthworms[b]	–	–	–
Pumps	39.2	39.2	8.70
Total	137.9	137.9	23.8

[a]From each manufacturer/supplier, including the way back.
[b]Assumed to be picked in nature near the WWTPs.

Table 3 | LCI results for the construction, operation and dismantling phases of the three WWTPs (per PE)

Flow	Unit	Reference solution			Alternative solution		
		SRI	CW	AS	SRI-VF	CW-VF	AS-VF
Construction phase							
Concrete[a]	kg	175.2	110.8	–	487.1	515.2	354.4
Gravel	kg	–	1.08×10^{4}	–	44.7	44.7	42.9
Sand[b]	kg	9.54	0.170	0.270	46.9	46.9	45.0
Steel (inc. stainless steel)	kg	–	–	24.28	4.1	18.2	3.0
Iron	kg	169.5	0.3400	7.100	206.0	661.7	625.2
Polypropylene	kg	0.121	0.643	–	8.07×10^{-3}	8.07×10^{-3}	7.75×10^{-3}
PVC	kg	0.034	3.17×10^{-3}	–	0.137	0.137	0.033
HDPE	kg	4.57	1.47×10^{-2}	–	7.92×10^{-3}	7.92×10^{-3}	1.90×10^{-3}
Sawdust	kg	–	–	–	7.46	7.46	7.16
Earthworms	kg	–	–	–	7.5	7.5	7.2
Fossil fuel (on-site machinery)	kg	0.386	0.698	0.278	0.386	0.698	0.278
Fossil fuel (electricity generator)	kg	0.498	0.902	0.360	0.498	0.902	0.360
Total fossil fuel	kg	0.884	1.60	0.638	0.884	1.60	0.638
Operation							
Raw wastewater	m^3	1,369.0	1,369.0	1,314.0	1,369.0	1,369.0	1,314.0
Emissions to water (COD)	kg	190.8	254.4	176.2	311.4	311.4	245.9
Emissions to water (TN)[c]	kg	39.8	76.3	63.2	77.4	77.4	55.0
Emissions to water (TP)[c]	kg	29.3	60.7	10.5	36.6	36.6	7.50
TN (in primary sludge)[d]	kg	–	4.88	4.88	4.88	4.88	4.88
TP (in primary sludge)[d]	kg	–	3.25	3.25	3.25	3.25	3.25
Sawdust consumption[e]	kg	–	–	–	74.3	74.3	71.3
Production of earthworms[f]	kg	–	–	–	0.75	0.75	0.72
Production of vermicompost	kg	–	–	–	16.3	16.3	15.6
Electricity consumption[g]	MJ	3,940.0	3,940.0	1.16×10^{6}	6,340.0	6,340.0	4,520.0
Dismantling							
Construction waste[h]	kg	2.43×10^{-5}*	1.77×10^{-4}*	–*	291.0	312.0	222.0
General waste[i]	kg	0.179*	1.309*	2.517*	0.119	0.119	0.114
Fossil fuel (on-site machinery)	kg	0.386	0.698	0.278	0.386	0.698	0.278
Fossil fuel (electricity generator)	kg	0.125	0.225	0.090	0.125	0.225	0.090
Fossil fuel (crushing machinery)	kg	–	–	–	0.664	1.200	0.479
Total fossil fuel	kg	0.510	0.924	0.368	1.170	2.130	0.848

[a]As pre-cast concrete.
[b]As quartz sand.
[c]In the reference solution, the distance suppression of the sawdust transportation was negligible. Total nitrogen in raw wastewater was established as 1.75 of the NH_4^+ emissions and total phosphorus as 1.67 of the PO_4^{3-} emissions (Henze & Comeau 2008).
[d]According with the values from Lourenço (2014).
[e]The application of sawdust during the packing renew.
[f]Biomass grow.
[g]Includes the electricity consumption for lights and, in the alternative solution, the electricity required to pump the wastewater from primary treatment and for effluent recirculation. The value for AS was adjusted from MJ to GJ due to inconsistency of original units.
[h]50% of the construction waste was assumed to be recycled by private companies (50% of concrete+gravel+steel+sand)).
[i]Stainless steel+PP+PVC+HDPE. In the reference situation, values from construction and general waste were the ones reported by Machado *et al.* (2007).

Emissions to water courses were computed for the chemical oxygen demand (COD), total nitrogen and total phosphorus. The accumulated COD emissions during operation were of 311.4 kg PE^{-1} in SRI-VF and in CW-VF, and of 245.9 kg PE^{-1} in AS-VF (Table 3), therefore between 22 and 63% higher than in the reference solution (190.8 kg PE^{-1} in SRI, 254.4 kg PE^{-1} in CW, and 176.2 kg PE^{-1} in AS). They are nonetheless about ten times lower than those reported for treatment plants of similar size (Hospido *et al.* 2008), so the emission of nutrients is already well optimized in the studied base and alternative solutions.

Electricity consumption in the reference solution varied from 3,940 MJ PE^{-1} in SRI and CW to 1.16×10^6 MJ PE^{-1} and, in the alternative solution from 4,520 MJ PE^{-1} in AS-VF to 6,340 MJ PE-1 in SRI-VF and CW-VF. The values of electricity were higher for SRI-VF and CW-VF comparing with SRI and CW due to the introduction of a new pump. It was lower in the alternative solution for AS due to the elimination of the air injection system. Electricity consumption is a key element in the overall environmental performance of a WWTP. In fact, energy use has been already identified as one of the major sustainable development indicators for wastewater treatment systems (Palme *et al.* 2005). Energy consumption in the reference solution and in the alternative are in line with values reported by other authors. Nie *et al.* (2013), in a study with tower VF to attend a served population of 230 PE, reported electricity consumptions in the range of 200 MJ PE^{-1} to 750 MJ PE^{-1}. Tillman *et al.* (1998) found, for a period of 30 years, for two small WWTPs in Sweden, electricity consumptions in the range of 228 MJ PE^{-1} to 576 MJ PE^{-1}. Hospido *et al.* (2008) studying thirteen small WWTPs in Galicia (Spain) found mean electricity consumptions in the range between 102 and 427.8 MJ PE^{-1}. Magar (2016) refers electricity consumptions during operation of 234 MJ PE^{-1} and 1,944 MJ PE^{-1} when managing three small WWTPs in Norway and De Feo *et al.* (2016) refer electricity consumptions of 4,320 MJ PE^{-1}, and Weiss *et al.* (2008) of 4.5×10^5 MJ PE^{-1}. Treating wastewater using VF, Laws (2003) refer electricity consumption in the range of 5.0×10^5 MJ PE^{-1} to 3.7×10^6 MJ PE^{-1}, due to the use of UV for disinfection. In fact, an increase of 30% in the total use of electricity can be expected when UV disinfection is used (Nie *et al.* 2013). Electricity demand in WWTPs is also influenced by the inflow since higher inflows show generally lower consumption per PE (Trapote *et al.* 2014), due to economies of scale in larger infrastructures, leading to larger but more efficient equipment, better performing automation, and better-trained staff operators CUAS (2015).

The total production of sludges during the operation period was the same on all WWTPs, equal to 1,100 kg PE^{-1}, which is similar to values referred by Laws (2003) for his VF study in Chile, of near 1,056 kg PE^{-1} (after correcting his moisture content to 80%). Magar (2016) refers sludge productions between 5.98 and 50 kg PE^{-1}, Hospido (2008) indicates productions in the range of 84.6 kg PE^{-1} to 717.3 kg PE^{-1}; and Tillman *et al.* (1998) in the range of 96.3 kg PE^{-1} to 768 kg PE^{-1}. The prediction of vermicompost production was 16.3 kg PE^{-1} in SRI-VF and in CW-VF, and 15.6 kg PE^{-1} in AS-VF (Table 3).

During the dismantling phase, the main difference between the base and alternative solutions resides in the need to dismantle the vermifilter, which resulted in an added amount of construction waste of around 300 kg PE^{-1}. Other unspecified waste was also created, but in small amounts (Table 3). During this phase, the heavy duty equipment and generator were responsible for the consumption of a substantially larger amount of fuel in the alternative solution than in the reference (about 900 times for SRI-VF; 540 times for AS-VF; and 90 times for CW).

4.2. LCIA

The construction, operation and dismantling of the WWTPs lead to positive net emissions of most selected LCIA indicators (Table 4). The exceptions were for a minor reincorporation of abiotic resources in AS and in all the alternative solutions during construction, which is due to the way how material recycling is accounted in CML's characterization factors. Due to the way how LCIA results are presented, the positive indicator values may correspond to negative environmental impacts, and the opposite to the negatives. We will refer throughout the text to the signal of impacts having these relationships in mind.

Considering the reference solution, the treatment showing worst impacts in most categories throughout the life cycle is CW due the impacts during the construction phase, followed by AS and SRI (sums of each phase are described in Table 4; see more detailed analysis in Supplementary Material). The only exception was OLD, where AS has marginally higher emissions of CFC-11 eq. made during the production of the stainless steel activated sludge prefabricated unit. In CW the construction phase contributes most to its life cycle impacts due to the earthworks involved, namely in building access roads, clearing, constructing basins and dikes, installing piping and valving, planting, seeding, liming, fertilizing, and mulching dikes and disturbed areas. In the remaining systems, operation is the phase where impacts are highest. Dismantling has the lowest impact in our simulations due to the assumption of recycling 50% of demolition wastes.

Table 4 | Results per impact category by each one of the three phases for the two scenarios (per PE)

			Impact result					
			Reference solution			Alternative solution		
Phase	Impact category	Reference unit	SRI	CW	AS	SRI-VF	CW-VF	AS-VF
Const	AD	kg Sb eq.	1.47×10^{-5}	2.20×10^{-4}	-8.26×10^{-4}	-9.93×10^{-5}	-5.76×10^{-4}	-7.22×10^{-5}
O&M			1.80	1.80	530.1	2.898	2.898	2.065
Dism			1.49×10^{-7}	2.20×10^{-7}	1.98×10^{-7}	1.14×10^{-7}	1.83×10^{-7}	2.98×10^{-7}
Sum			1.800	1.800	530.099	2.989	2.897	2.065
Const	AC	kg SO_2 eq.	0.0451	8.21	0.165	0.196	0.280	0.113
O&M			0.790	0.321	6.190	0.190	0.190	0.953
Dism			1.75×10^{-3}	3.17×10^{-3}	1.26×10^{-3}	2.23×10^{-3}	3.10×10^{-3}	4.90×10^{-3}
Sum			0.837	8.53	6.36	0.388	0.473	1.07
Const	EUT	kg PO_4^{3-} eq.	7.7×10^{-3}	1.83	0.0248	0.037	0.048	0.0197
O&M			13.1	24.3	20.7	8.92	8.92	7.49
Dism			1.84×10^{-4}	3.33×10^{-4}	1.33×10^{-4}	3.90×10^{-4}	4.93×10^{-4}	7.62×10^{-4}
Sum			13.1	26.1	20.7	8.96	8.97	7.51
Const	FWT	kg 1,4-DB eq.	0.433	40.4	0.9977	1.75	1.81	0.459
O&M			0.270	3.19	2.15	0.106	0.106	0.964
Dism			3.80×10^{-3}	6.88×10^{-3}	2.74×10^{-3}	2.42×10^{-3}	4.14×10^{-3}	6.82×10^{-3}
Sum			0.707	43.6	3.15	1.86	1.92	1.43
Const	GWP	kg CO_2 eq.	23.0	1.78×10^{3}	46.3	81.7	108	52.7
O&M			39.5	150	218	26.4	26.4	130
Dism			0.234	0.425	0.169	0.396	0.520	0.811
Sum			62.7	1.93×10^{3}	264	108	135	183
Const	HT	kg 1,4-DB eq.	6.63	349	3.47	22.5	24.5	11.4
O&M			3.43	2.88	33.1	2.57	2.57	16.8
Dism			0.038	0.068	0.027	0.041	0.059	0.094
Sum			10.1	352	36.6	25.1	27.1	28.3
Const	MAEC	kg 1,4-DB eq.	213	2.47×10^{4}	463	770	102	469
O&M			411	1.11×10^{3}	4.67×10^{3}	495	495	5.93×10^{3}
Dism			11.0	20.0	7.95	9.78	15.0	24.1
Sum			635	2.58×10^{4}	5.14×10^{3}	1.28×10^{3}	612	6.42×10^{3}
Const	OLD	kg CFC-11 eq.	4.32×10^{-7}	9.96×10^{-6}	1.11×10^{-6}	1.38×10^{-6}	2.08×10^{-6}	9.96×10^{-7}
O&M			2.93×10^{-6}	2.4×10^{-6}	3.39×10^{-5}	2.4×10^{-6}	2.94×10^{-6}	7.33×10^{-7}
Dism			6.04×10^{-10}	1.10×10^{-9}	4.36×10^{-10}	8.40×10^{-10}	1.15×10^{-9}	1.80×10^{-9}
Sum			3.36×10^{-6}	1.24×10^{-5}	3.50×10^{-5}	3.78×10^{-6}	5.02×10^{-6}	1.73×10^{-6}
Const	PO	kg C_2H_4 eq.	3.89×10^{-3}	0.594	0.019	0.017	0.027	0.010
O&M			0.013	0.047	0.084	9.79×10^{-3}	9.97×10^{-3}	0.051
Dism			1.42×10^{-4}	2.58×10^{-4}	1.03×10^{-4}	1.69×10^{-4}	2.40×10^{-4}	3.80×10^{-4}
Sum			0.017	0.641	0.103	0.027	0.037	0.061
Const	TE	kg 1,4-DB eq.	0.020	0.527	0.060	0.091	0.125	0.064
O&M			0.019	0.021	0.220	0.021	0.021	0.235
Dism			0.011	0.019	7.64×10^{-3}	5.93×10^{-3}	0.011	0.018
Sum			0.050	0.567	0.288	0.118	0.157	0.317

Negative values indicate removal of the indicator substance, therefore a positive impact.

Const., Construction phase; O&M, Operation phase (values for 30 years); Dism., Dismantling phase; Sum, Sum of all three phases.

[a]Values or the original WWTP with VF.

[b]Values of the original WWTP with the original secondary treatment.

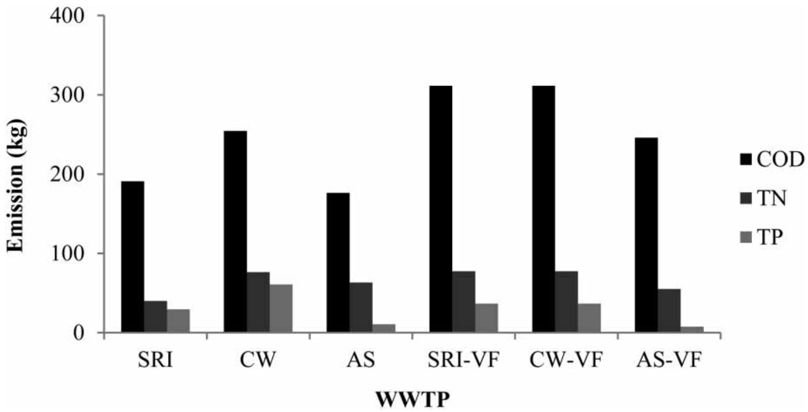

Figure 2 | Total COD, TN and TP emissions for operation for the WWTPs.

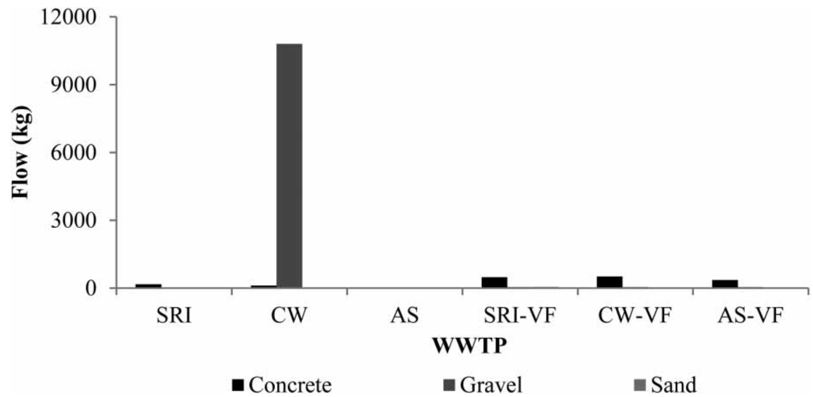

Figure 3 | Concrete, gravel and sand consumptions for the WWTPs studied.

In the alternative solution, the replacement of the constructed wetland or of the activated sludge by the vermifilter seems to bring important environmental benefits, as reflected in an improvement in most impact categories, in particular in the construction phase. This is due to VF being less energy-intensive of inputs such as steel and plastic materials. The substitution of slow rate filtration by the vermifilter results in the improvement of indicators AC and EUT, but in the deterioration of the remaining indicators. Thus, the vermifilter would be a better environmental solution than CW and AS in the studied WWTPs and according to the performances obtained by the impact categories, a more sustainable solution (Hannouf & Assefa 2018).

A more detailed analysis shows that during the operation phase, the vermifilter has lower impacts than the remaining solutions in most impact categories. The exceptions are in AD, with the indicator worsening between one and two orders of magnitude (2.898 kg Sb eq. PE^{-1} in SRI-VF and CW-VF, and 2.065 kg Sb eq. PE^{-1} in AS-VF); and MAEC and TE, with only marginal deterioration of the indicators' values (for MAEC 495 kg 1,4 DB eq. in SRI-VF and CW-VF, and 5.93×10^3 kg 1,4 DB eq. in AS-VF; and for TE 0.021 kg 1,4 DB eq. in SRI-VF and CW-VF, and 0.235 kg 1,4 DB eq. in AS-VF). The higher emissions of COD (311.4 kg PE^{-1} in SRI and CW, and 249.9 kg PE^{-1} in AS-VF), but lower of nutrients (77.4 kg TN PE^{-1} in SRI-VF and in CW-VF, and 55.0 kg PE^{-1} in AS-VF; and 36.6 kg TP PE^{-1} in SRI-VF and in CW-VF, and 7.50 kg PE^{-1} in AS-VF) in the alternative may help justify these differences.

Studies report the high relative weight of operation phase impacts of WWTPs being usually electricity and sludge management the most important flows during operation (De Feo & Iuliano 2016). Several authors even assume that the contribution of construction and dismantling is negligible if compared with operation, especially during a relatively long lifetime (Corominas *et al.* 2013). Our results, on the contrary, show that for very small WWTPs the impacts of the construction phase do not dilute enough throughout the lifecycle and number of served inhabitants, unlike the economies of scale of larger facilities.

Dismantling was the phase which contributed less for the impact categories on both solutions, being in some categories negligible or even zero.

This research aimed to find the usefulness of that the results found, especially the fact that the replacement of constructed wetland or activated sludge by vermifilter, in construction phase, seems to reflect in an improvement in most of the environmental impact categories. In the operation phase, the VF has lower environmental impacts than the remaining solutions for most impact categories. Future studies should include social and economic analysis and improve the LCA analysis with a full perspective of circular economy.

5. CONCLUSION

This study made a full comparative life cycle impact assessment for nature-based solutions for wastewater treatment in rural areas where a slow rate filtration plant, a constructed wetland, and an activated sludge (designated reference solution), were all evaluated as were, and after substitution of the secondary treatment by vermifiltration (alternative solution). Detailed life-cycle inventory was obtained for each solution, which showed that more material resources are used during construction than in any other phase. Given the small served population, the material intensity (per PE) was higher than that found in other larger facilities. On the contrary, electricity was the resource more used during operation, which was an expectable result. They are more aligned with consumption rates found elsewhere, indicating that the operation of the facilities follows standardized procedures, therefore with little optimization freedom.

The replacement of constructed wetland by vermifiltration as secondary treatment seems to bring important environmental benefits in most impact categories, in particular in the construction phase. The replacement by VF in facilities with SRI seems to result in the improvement of some of the impact categories, in particular in the operation phase. As for dismantling, no conclusive results were obtained for the replacement by VF.

Our results show that the impacts during the construction phase outweigh those of the other phases when the number of served inhabitants is small, due to lack of economies of scale for all the scenarios. The use of vermifiltration as alternative secondary treatment, in particular to constructed wetlands and activated sludge would help reduce the impacts of several environmental categories. VF would be a better environmental solution than CW and AS in the studied WWTPs. We should note here that, as in all LCA studies, the results can be affected by the specificity of local conditions. These were minimized here as far as possible by setting the appropriate limits for the boundaries of the systems.

Life-cycle impact assessment provides but another measure of environmental sustainability and efficiency of alternative technologies, which should complement socio-economic and technological constraints (Lourenço & Nunes 2020).

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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