LIFE CYCLE ASSESSMENT OF WASTEWATER TREATMENT OPTIONS FOR SMALL AND DECENTRALIZED COMMUNITIES: ENERGY-SAVING SYSTEMS VERSUS ACTIVATED SLUDGE

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ABSTRACT

There are several methodologies that enable direct comparison of centralized and decentralized sewage treatment systems, both in economical and ecological view. One of the latter is the so-called Life-Cycle Analysis (LCA), which accounts for the environmental impacts of a product, service, or process over the course of its life cycle. Assessed environmental impacts generally include consumption of land, energy, water, and other resources as well as the release of substances (harmful and beneficial) into air, water, and soil. LCA is largely quantitative in nature and thus can help in selecting strategies that solve environmental problems rather than merely shifting them back and forth.

In the present study, an LCA comparison of several treatment processes for small and decentralized communities is made. The LCA focused on the construction, operation and disassembling phases of two energy-saving or natural systems (constructed wetland and slow rate infiltration) and a conventional one (activated sludge). The lower environmental impact of natural wastewaters treatment plants was clearly demonstrated using several ecologic indicators (e.g.: Global warming), confirming that decentralized technologies are advantageous, mainly because they require less resources.

KEYWORDS

Life Cycle Assessment; Wastewater treatment; Constructed wetland; Slow rate infiltration

INTRODUCTION

Anthropogenic activities generate environmental impacts that should be minimized to protect the quality of the environment, to preserve the ecosystems and to optimize the use of natural resources. In this context, Life Cycle Assessment (LCA), estimating the environmental impacts associated with a system (product, process or activity) from “cradle” to “grave”, that is beginning with the extraction of raw materials, used in the system, and ending with dismantling and final disposal, constitutes an environmental management tool with increasing application in conception and project of systems in a perspective of sustainability (Jensen *et al*., 1997). The ISO 14040:1997 standard has been the base for the realization of LCA studies, containing its general and methodological principals (Ortiz, 2006). In particular, the ISO 14041:1997 standard – *Definition of objective, scope and inventory analysis*, the ISO 14042:1997 standard – *Environmental impact assessment*, and the ISO 14043:1997 standard – Interpretation, detail the methodology underlying LCA studies. The different phases of the LCA methodology are schematically represented in Figure 1.

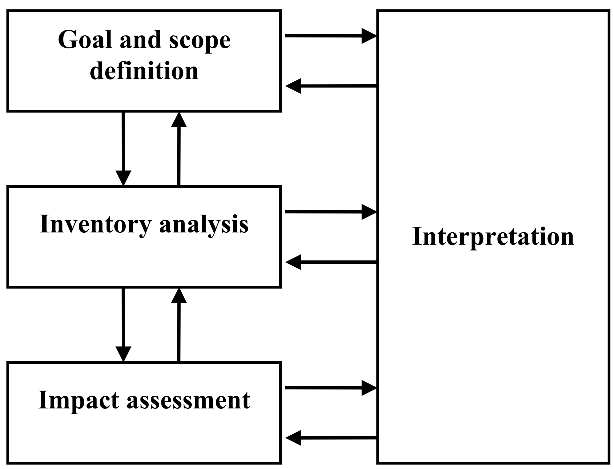


Figure 1. Phases of a LCA (ISO 14040, 1997)

The *goal* and *scope* definitions should be clear and consistent with the expected application of the LCA study. The scope definition should consider and describe the functional unit used in mass an energy balances, the system boundaries (conceptual, geographical and temporal), the type and extension of impact assessment, the data necessary to characterize the system, and the limitations of the study (Ortiz, *et al*., 2006). In turn, the *inventory analysis* is the process of collecting and analyzing data in order to quantify the inputs and outputs of the system, corresponding to the use of resources (energy and raw materials) and to the release of emissions (air, water, soil) for the entire life cycle of the system. In the *impact assessment* phase, the emissions catalogued in the inventory analysis are translated into their potential effect in the environment. Generally, this process consists in establishing the links between the use of resources and the release of emissions, identified in the inventory analysis, to the respective specific impacts in order to interpret, in the next phase, their effects. Finally, the information from the inventory and/or impacts assessment phases, presenting the critical sources of impacts, is appreciated in the *interpretation* phase in order to produce conclusions and recommendations. Interpretation involves a review of all the stages in the LCA process, in order to check the consistency of the assumptions and the data quality, in relation to the *goal* and *scope* of the study. It is important to remark that this phase has a subjective nature, since it is necessary to attribute relative weights to the different categories of environmental impact.

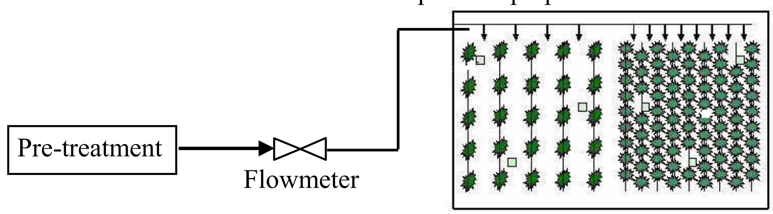
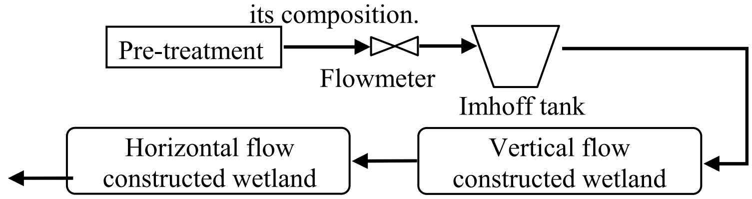
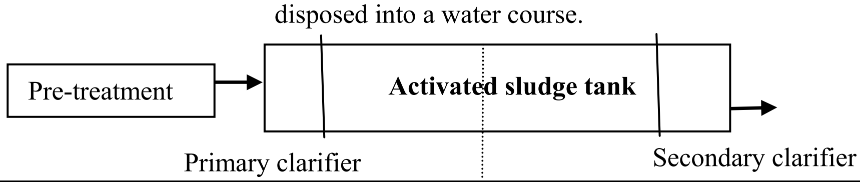
Wastewater treatment systems have been designed to minimize the environmental impacts of discharging untreated wastewater in natural aquatic systems. Different wastewater treatment options have different performance characteristics and also different direct impacts in the environment. Some systems have a higher energy usage, some use materials which have a high embodied energy (e.g. plastics), others occupy a greater expanse of land. If minimization of environmental impacts is one of the main functions of wastewater treatment systems then they should be designed so that their total impact on the environment is reduced (Dixon *et al*., 2003). Presently, given the long-term need for ecological sustainability, the goals for wastewater treatment systems need to move beyond the protection of human health and surface waters to include minimizing loss of scarce resources, reducing the use of energy and water, reducing waste generation, and enabling the recycling of nutrients (Lundin *et al*., 2000).

Recently, LCA has been used to explore the sustainability of wastewater systems, allowing the comparison of different technical solutions in terms of the estimated environmental loads (Emmerson *et al*., 1995; Dennison *et al.*, 1999; Tillman *et al.*, 1998; Dixon *et al*., 2003; Palme *et al*., 2005). In this context, it is the aim of this work to identify, quantify and compare the environmental impacts associated with three alternative systems for wastewater treatment, namely Constructed wetland, Slow rate infiltration and Activated sludge, using a LCA methodology.

METHODS

1. Wastewater treatment systems

The wastewater treatment systems included in the scope of the present work, Constructed wetland, Slow rate infiltration and Activated sludge, are described briefly in Figure 2.

System	Population (p.e.)	Flowrate (m^3/d)	Description
Slow rate infiltration[1]	40 (Winter) 120 (Summer)	5 (Winter) 15 (Summer)	The system occupies an area of 2000 m^2 and is planted with *Populus euroamericana* (40) and *Eucaliptos camaldulensis* (214). The irrigation system is made of PE tubes. The trees will be cut each 5 years and the wood shredded in order to be later used to produce pulp. 
Constructed wetland[1]	120	15	Two Constructed wetlands (vertical flow, 317 m^2, and horizontal flow, 277 m^2) planted with *Phragmites australis*. The following materials are included in the system: i) geotextil membrane, to waterproof the soil; ii) gravel, used as a support for the biomass growth; iii) polymeric tubing's (PE, PP and PVC); iv) Imhoff tank (concrete and PVC). Biomass requires annual culling and the green waste is sent to a landfill. The sludge accumulated in the Imhoff tank is removed every 10 years and considered a soil corrector due to its composition. 
Activated sludge[2]	500	60	The activated sludge is made of Inox Steel and has 2 aerators, functioning for 11 hours each. The sludge purged from the settling area was treated and used as a soil corrector. Effluent from the clarification area is disposed into a water course. 

[1]Experimental Plant of wastewater tratment, Carrión de los Céspedes (Spain); [2] Municipal wastewater treatment plant (Portugal)

Figure 2. Description of the wastewater treatment systems.

2 Application of LCA to wastewater treatment systems

The comparison between different wastewater systems designed for low population areas was performed using the Life Cycle Assessment methodology with data available from systems currently in operation and considering a 20 year life cycle.

The LCA of the aforementioned wastewater treatment systems was carried out using the software *SimaPro* (Pré – Product ecology consultants) (Manual of Simapro). *SimaPro* can be used in the design of LCA systems and in the calculation of the contribution of several emissions to an impact category, according to the characterization method chosen. Several emissions databases are included in the software, as well as, various methods of characterization emissions. Additionally, it allows the introduction of new emission data. Figure 3 presents schematically the integration of SimaPro in LCA assessment.

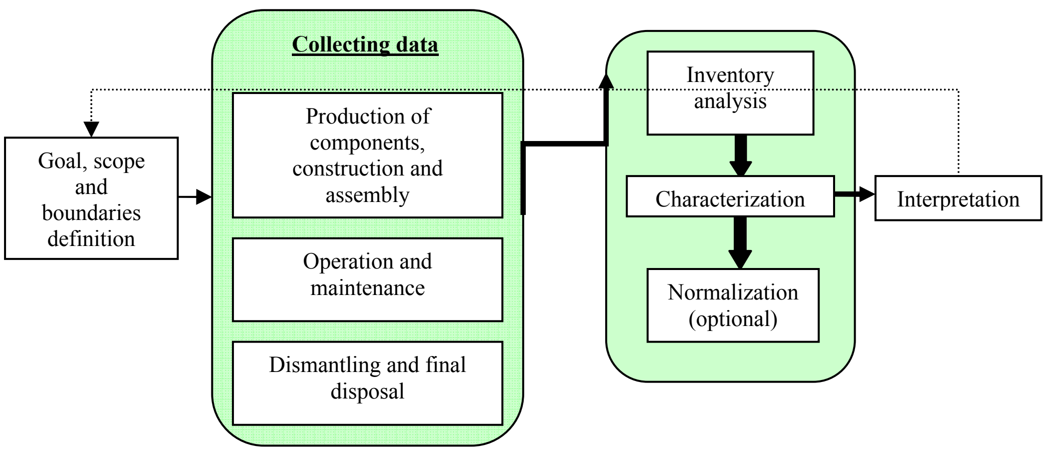


Figure 3. Integration of SimaPro and LCA.

The functional unit adopted in the present LCA study was 100 population equivalent (p.e.). The data reports to the production of components (equipments and accessories), construction, assembly, operation, maintenance and, at last, dismantling and final deposition. And it refers to the amounts of materials used, fuels

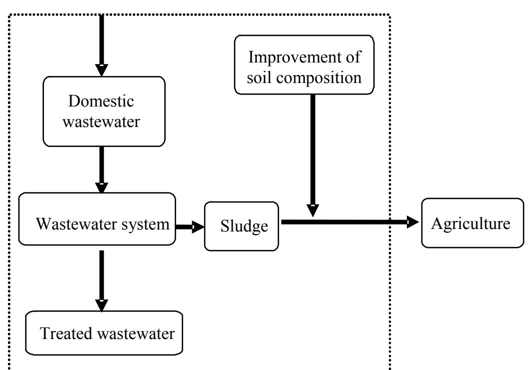


Figure 4. Wastewater treatment systems

and processes involved. Figure 4 depicts the system boundaries chosen for the present study.

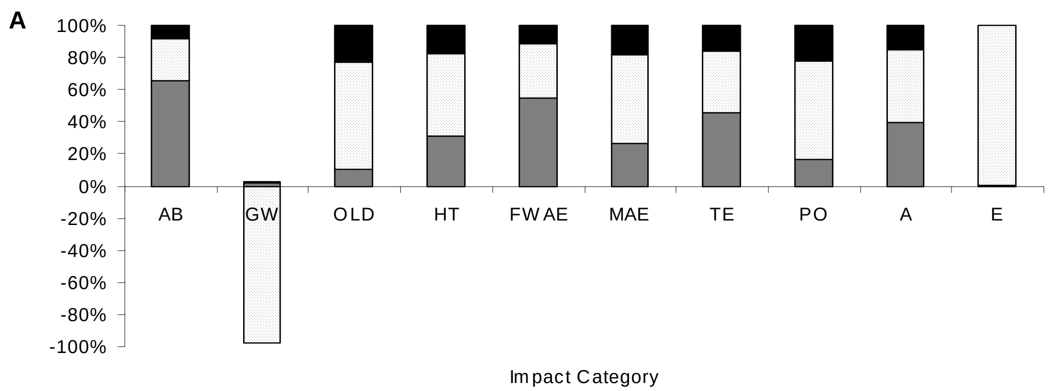
All materials, fuels and processes considered in the life cycle of the three wastewater treatment systems studied were collected in the *inventory analysis* phase and the respective emissions characterized using SimaPro. It was assumed that the materials were disposed off in a municipal landfill after the dismantling phase. In the *impact assessment* phase the collected emissions, in the previous phase, were converted into their potential environmental impacts through impact categories. This process includes both stages, characterization and normalization. In this study the *characterization method CML 2 Baseline 2000* was chosen since it is one of the few which includes characterization factors for the emissions of phosphorous, nitrogen and organic matter. It follows ISO 14000 guidelines concerning the impact categories and considers the following descriptors: *abiotic depletion* (AD), *global warming* (GW), *ozone layer depletion* (OLD), *human toxicity* (HT), *fresh water aquatic ecotoxicity* (FWAE), *marine aquatic ecotoxicity* (MAE), *terrestrial ecotoxicity* (TE), *photochemical oxidation* (PO), *acidification* (A) and *eutrophication* (E). The aggregation of the emissions in each descriptor was done using characterization factors that compare the effect of a specific emission with that of a reference emission[1]. The *normalization phase* was used to compare the different impact categories in absolute numbers, using the average global emissions per capita. Each value is divided by the average worldwide emission of that substance per total world population.

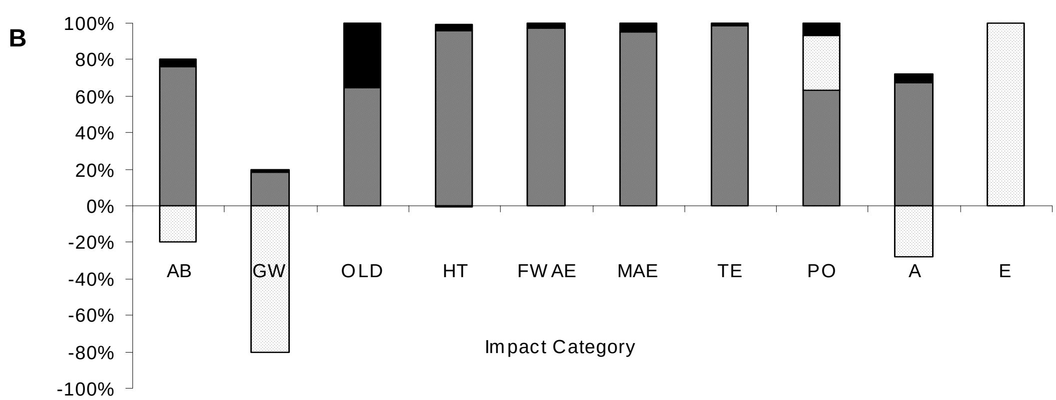
RESULTS AND DISCUSSION

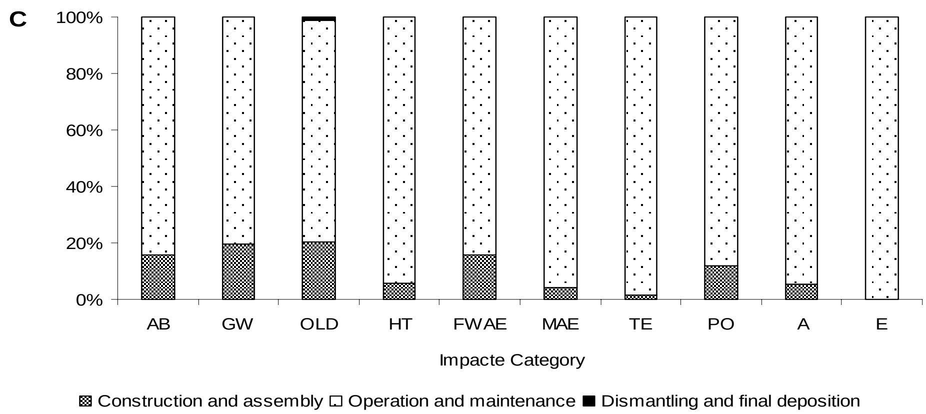
The relative contribution of each stage of the life cycle of the different wastewater treatment systems studied, for the several environmental impact categories observed, is presented in Figure 5. The results' analysis reveals that the *dismantling and final deposition* stage, the last in the life cycle, corresponds to the least environmental impact in each of the treatment systems. This result is congruent with the findings of Dixon *et al*., 2002. Thus, the high energy consumption (22 h/d) is the main responsible for the environmental impact of the Activated sludge treatment during *operation and maintenance* phase. In the Slow rate infiltration, the impact is associated with the cutting of the eucalyptus every 5 years, and their grinding for later use in the manufacture of paper pulp. It is remarkable that the *operation and maintenance* stage is the only contributor to the *eutrophication* impact category, since the discharge of the treated wastewater (which still contains some contaminants) into the superficial aquatic

[1] For example, in the case of the impact category Global warming, all contributing emissions are converted in equivalents of CO_2.

medium, is exclusively taken into account at this stage of the life cycle. During *operation and maintenance* the emissions considered were due to the flow of treated wastewater (which still included a small amount of phosphorous, COD and ammonia) directly to a superficial aquatic medium. It was considered that the three treatment systems removed enough contaminants so that the emissions complied with Portuguese legislation (Diário da Republica). The first stage of the life cycle, *construction and assembly*, shows the greatest impact in the Constructed wetlands. To the *operation and maintenance* stage, the longest one, the most relevant impact derives from the annual cutting of the *Phragmites australis*.







AB	Abiotic depletion	GW	Global warming
OLD	Ozone layer depletion	HT	Human toxicity
FWAE	Fresh water aquatic ecotoxicity	MAE	Marine aquatic ecotoxicity
TE	Terrestrial ecotoxicity	PO	Photochemical oxidation
A	Acidification	E	Eutrophication

Figure 5. Contribution of the life cycle stages of the various treatment systems studied in the various impact categories: A) Slow rate infiltration, B) Constructed wetlands and C) Activated sludge systems. The impact categories shown are those considered in the CML 2 Baseline 2000 method.

The environmental impact of the treatment systems during their life cycles, considering a 20 year operational life were compared (Figure 6). Also, in order to better understand the impact of the treatment systems, an extreme scenario was considered, the hypothetical discharge of untreated wastewater directly into a superficial aquatic medium.

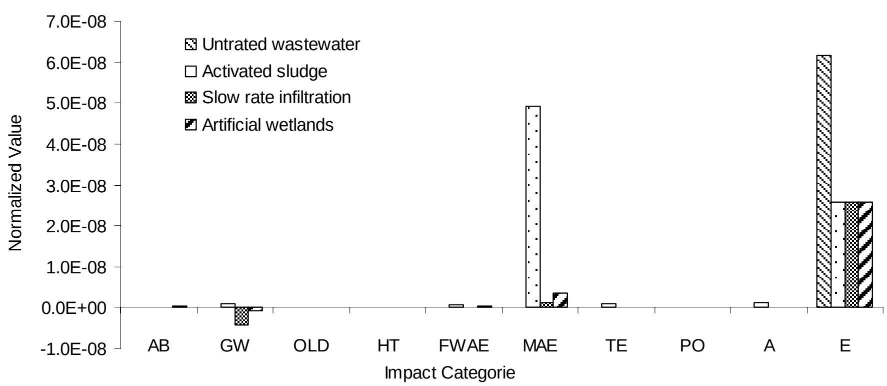


Figure 6. Environmental impact of domestic wastewaters produced by 100 P.E., either treated or discharged untreated, into a superficial aquatic medium. The impact categories shown are those considered in the CML 2 Baseline 2000 method.

The impact described in the *eutrophication*, resulting from the discharge of the effluent in surface waters, is significantly lower for the discharge of treated wastewater when compared to the untreated one. This result is related to the lower concentrations of organic carbon, nitrogen and phosphorous present in the treated effluent. The manufacture/production processes of the materials used in the construction of the treatment systems were the principal contributors for the *toxicity* and *ecotoxicity* impact categories. Of particular note the higher impact of the Activated sludge process ($5.13 \cdot 10^{-8}$) associated with the emission of heavy metals, connected with the production process of the steel used in the construction of the activated sludge tank. The difference between the sum of the *ecotoxicity* and *toxicity* impacts of the Constructed wetlands ($3.97 \cdot 10^{-9}$) and Slow rate infiltration ($1.22 \cdot 10^{-9}$) systems can be explained through the larger amount of materials used in the construction and assembly of the first system. Finally, it is important to stress that the Activated sludge system is the only one which shows a meaningful impact in *marine toxicity*. The main contributor to the impact category *abiotic depletion* is the consumption of fuel and energy in each of the life cycles of the treatment systems. Both, the Slow rate infiltration and the Constructed wetlands, present a similar value for this descriptor, $2.48 \cdot 10^{-10}$ e $3.05 \cdot 10^{-10}$ respectively, and approximately 10 times smaller than the Activated sludge system, $2.04 \cdot 10^{-9}$. The natural treatment systems, particularly the Slow rate infiltration system, contribute to the diminishing of *global warming*, the absorption of CO_2 by the plant biomass translates into a reduction of this impact category of $-4.25 \cdot 10^{-9}$ for the Slow rate infiltration and of $6.76 \cdot 10^{-10}$ for the Constructed wetlands. Conversely the Activated sludge process increased *global warming* by $9.11 \cdot 10^{-10}$ during its life cycle. The impact of the various treatment systems in the categories *ozone layer depletion* and *photochemical oxidation* is considerably lower than those of the other descriptors. The *acidiphication* impact category shows only a relevant negative value for the Activated sludge system.

As a conclusion, the main advantages of energy-saving treatment systems, Slow rate infiltration and Constructed wetland, relatively to the Activated sludge system, lays on the lower use of materials in the *construction and assembly*, using less energy in the *operation and maintenance* phase and contributing to the reduction of Global warming due to the absorption of carbon dioxide, as opposed to the Activated sludge system.

CONCLUSIONS

In the field of environmental assessment, the methodology of Life Cycle Assessment, integrated in to the software tool SimaPro 7, allowed the identification of the main impacts of the treatment systems (namely the Global warming) without dispensing the necessity of databases research, which enriched its analysis. Presently it is considered that LCA is becoming more relevant as a decision support tool for designers and municipal sewage systems managers

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