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Life cycle assessment applied to wastewater treatment plants: how the choice of background processes can affect the studies' reliability

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ABSTRACT

Considering the lack of transparency and representativeness of the data, one of the main challenges for the application of the life cycle assessment (LCA) to wastewater treatment plants (WWTP) is to improve the quality of the inventories. Most of the works published in the technical or scientific literature show that life cycle inventories (LCI) are not detailed, which makes it difficult to identify what is actually included and which background processes were used in the database. Therefore, even though the LCA can be applied to assess the environmental performance of a WWTP, it does not mean that the studies are reliable, especially in developing countries. This paper investigates how the choice of background processes in the database can affect and reduce the reliability levels of the LCA applied to a WWTP. Sensitivity analysis was used and the impact categories were those available in the (Leiden Centre of Environmental Science) CML method (one of the well-established methods for WWTP environmental performance investigation and the one most applied in LCA relating to these facilities). The study highlights the importance of specifying the background processes used as a requirement for improving the LCA studies. Additionally, a good practice when elaborating LCI is recommended, with the aim of ensuring that the results can be carefully analyzed before being used by decision-makers.

Keywords: Background database; Life cycle assessment; Reliability; Sensitivity analysis; Wastewater treatment plant

1. Introduction

Life cycle assessment (LCA) has been a widely applied approach to evaluating the environmental impacts of different wastewater treatment plants (WWTP) around the world. LCA is reported to be a valuable methodology for evaluating the WWTP's performance beyond the trade-off between process efficiency and final effluent quality since it includes resource and energy consumption, air emissions, and waste generation.

Despite a large number of scientific publications, there is variability in the methods used and results derived from LCA when applied to WWTP. Examples include the functional unit used (e.g., the volume of treated wastewater or equivalent population), the choice of the impact assessment method or categories, assumptions about the inclusion of sewage collection and transportation network, sludge treatment, and the analysis of the construction phase [1].

The majority of the scientific papers published between the years 2003 and 2018 showed that there are still many

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limitations in using LCA to evaluate environmental impacts from WWTP. Quality of data (representativeness, integrity, and reliability), transparency of the criteria used during the elaboration of inventories, the choice of the functional unit, and the reproducibility of the results are some of the gaps that need to be overcome. Several LCA applied to WWTP do not present the background processes in the database, which makes it very difficult to identify what was actually considered in the study and, therefore, may compromise the validity of the results [2–5].

The lack of transparency in the LCA studies influences the quality of the results and may result in the discrediting of this methodology. If the data is transparent and reliable, the reviewers and decision-makers can identify failures and then be more assertive. Inventory data should be indexed, inter-operable, re-usable, and have open access [6]. The European Commission (EC) and the U.S. National Science Foundation (NSF) go further and request that the data from publicly funded research be made open and re-usable.

Another important requirement is to obtain the WWTP's full-scale data to ensure the representativeness of a regional database and this can be difficult in developing countries. Inventory data are collected from a variety of sources and some LCI studies have focused on data that have been collected directly from research, experiments, and laboratory measurements [1]. Studies that use international database results lack information and so do not provide an exact scale or explain the background processes from the databases that were used. In general, information from the background process, which includes the production of chemicals and building materials, are provided by international databases like Ecoinvent©, for example, and this assumption reduces the reliability of the studies.

A recent review of the LCA applied to WWTP in developing countries points out that description of the sources and technical parameters, as well as the elaboration of local databases associated with easier access to the background processes databases and LCA software, could significantly increase the quality of the studies [7]. The authors list the challenges for developing and developed countries, and the requirements for inventories that show detailed LCI (with sources and background data) in the LCA of wastewater treatment.

About 62% of the papers analyzed do not present the life cycle inventory (LCI), and about 50% of the papers did not include inventory data at all, while 20% included partial inventory data. Unfortunately, the absence of a detailed LCI does not permit verification of the correlation of all input and output flows with the functional unit (FU) and the life cycle impact assessment (LCIA) results. Therefore, some flows that were cataloged in the LCI, are not very accurate and cannot translate their potential impact on the different environmental compartments [1,7].

Lopes et al. [8] performed an LCA to evaluate the environmental performance of the construction and operation phases of a full-scale WWTP, composed of a UASB reactor followed by constructed wetlands. In a preliminary assessment, the authors found a high uncertainty level for water emissions due to the use of data from the literature.

Therefore, this paper proposes to deepen the investigation on the uncertainty of the background data choiced for the elaboration of the WWTP's LCI published by Lopes et al. [8]. Specifically, aim to answer the following research question: how can the choice of background processes in the database affect and reduce the reliability levels of the LCA applied to a WWTP?

2. Methods

2.1. LCA goal and scope

The LCA was performed on a full-scale WWTP designed to treat domestic wastewater, according to ISO recommendations [9]. The process consists of an anaerobic reactor (an upflow anaerobic sludge blanket (UASB)) followed by four constructed wetland beds (CW) and a disinfection step with the application of sodium hypochlorite solution (NaOCl). The WWTP has been operating properly since 2008, treating the wastewater from 250 residences. More details on WWTP can be found in Lopes et al. [8].

Two system boundaries were defined (Fig. 1). The initial system boundary plan included a quantitative inventory of the wastewater treatment process (e.g., building materials, direct air emissions, chemicals, energy consumption, and discharge of the treated effluent). The second system boundary plan used the original background process data from datasets available at Ecoinvent© version 3.1, using the system model "allocation and default" as the unit process, with links to other processes (data from materials, chemical, and energy production) and the Global (GLO) and Rest of the World (RoW) geographical scope (available in SimaPro© 8.1).

2.2. Life cycle inventory

The LCI data covered the following aspects: construction materials, energy and chemical consumption, air, and water emissions. Data from the WWTP engineering projects and information from the websites of manufacturers and construction material suppliers were crucial to the elaboration of the LCI of the construction phase. The LCI of the operation phase considered the flow rate, physicochemical characteristics of the influent and effluent, the energy and chemical consumption, air emissions, equipment, and process specifications.

The operational report of this WWTP showed that it is necessary to replace the support material (gravel) of each constructed wetland bed every five years to prevent clogging. Therefore, three substitutions were considered during the life cycle of the WWTP. The total amount of gravel removed from the constructed wetland beds was taken into account in the LCI of the operation phase, as final waste.

The characteristics of the raw wastewater and the treated effluent were obtained by collecting composite samples and conducting laboratory analyses over a period of 8 months [8]. The following parameters were used to characterize the wastewater: biological oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), ammonia, total Kjeldahl nitrogen (TKN), nitrate, total phosphorus, and residual chlorine (Table 1).

Some assumptions were made in the study. The transportation of construction materials was not accounted for in the first system boundary plan because of the lack of

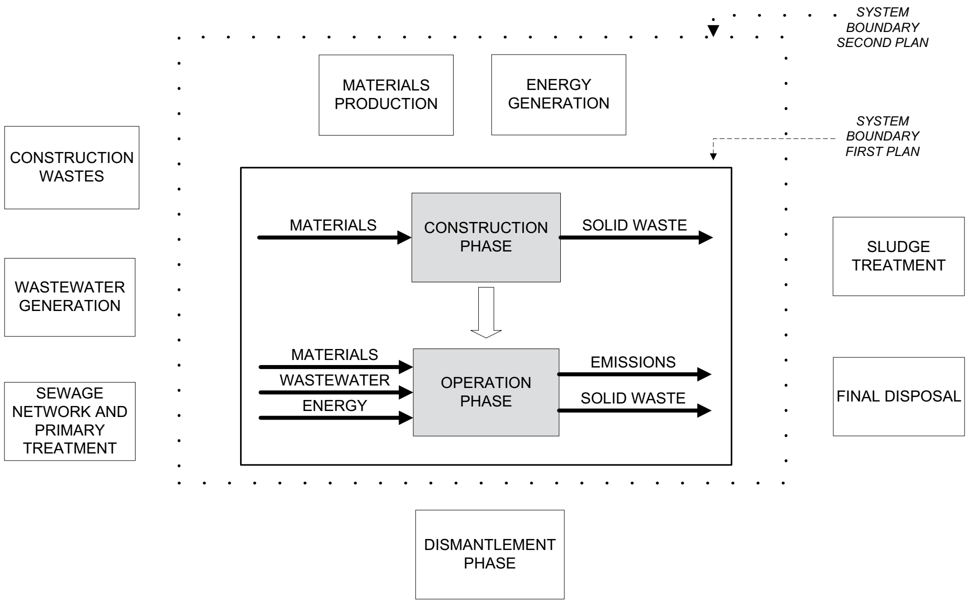

Fig. 1. LCA system boundaries.

Table 1
Mean value of physicochemical parameters monitored in the WWTP

Parameters	Inlet	Outlet	Removal
BOD_5 concentration, mg O_2 L^{-1}	321.5	21.3	93%
COD concentration, mg O_2 L^{-1}	767.8	95.5	88%
TSS concentration, mg TSS L^{-1}	278.0	18.0	94%
Ammonia as N, mg N–NH_3 L^{-1}	41.3	39.5	4%
Total Kjeldahl nitrogen, mg TKN L^{-1}	46.2	45.7	1%
Total phosphorous, mg TP L^{-1}	7.3	7.9	–
Nitrate, mg N–NO_3^- L^{-1}		1.8	–
Chlorine, mg Cl_2 L^{-1}		0.8	–

data and since its contribution represents a minor fraction of the overall impact [10,11]. The discarding, processing, and operation of the biological sludge stabilization were not considered and the wetland plants are sent to landfill.

The air emissions, sludge, and methane dissolved from the UASB reactor were calculated from the mass balance of the COD fractions [12]. Air emissions (CH_4 and N_2O) from the constructed wetlands were obtained by the equations reported by the Intergovernmental Panel on Climate Change [13]. Table 2 shows the LCI of a full-scale WWTP, for its construction and operation phases.

2.3. Life cycle impact assessment

The impact assessment was carried out using the (Leiden Centre of Environmental Science) CML 2 baseline 2000 impact assessment method, which has been frequently used for all midpoint impact categories [14,15] and is the most-applied in LCA related to WWTP in developing countries [7]. The contribution analysis was used for the interpretation of the LCIA.

With the aim of evaluating how the choice of a background process available in databases like Ecoinvent© affects the results of an LCA applied on a local level, the background processes were chosen, taking into account the most representative geographical scope for the reality of a developing country located on South America. Choosing the GLO means global and represents activities, which are considered to be an average valid for all countries in the world; RoW represents the rest-of-the-world and BR (Brazil). However, this choice certainly influences the reliability of the LCA and the purpose of this paper is to investigate how.

Sensitivity analysis was performed by means of different calculations substituting similar background processes available in the Ecoinvent© database (sawnwood, hard wood, raw, and kiln dried/RoW was compared to sawnwood, parana pine from sustainable forest management, and kiln dried/BR, for example).

3. Results and discussion

3.1. Analysis of capital goods background process

The availability of inventories of capital goods, such as building materials and infrastructure, is still limited in developing countries. Therefore, additional effort is often required in data collection and this may be more complex than the elaboration of the LCA itself. So, using processes that are previously registered in existing databases such as Ecoinvent© is a very common practice despite the reduced reliability of the results. Considering the variety of background processes available in the Ecoinvent© database, it is necessary to choose the ones closer to the reality of the local study.

Taking into account the LCI data from Table 2, similar sawnwood background processes were analyzed by the share of total impacts for the WWTP construction phase. The results are presented in Fig. 2.

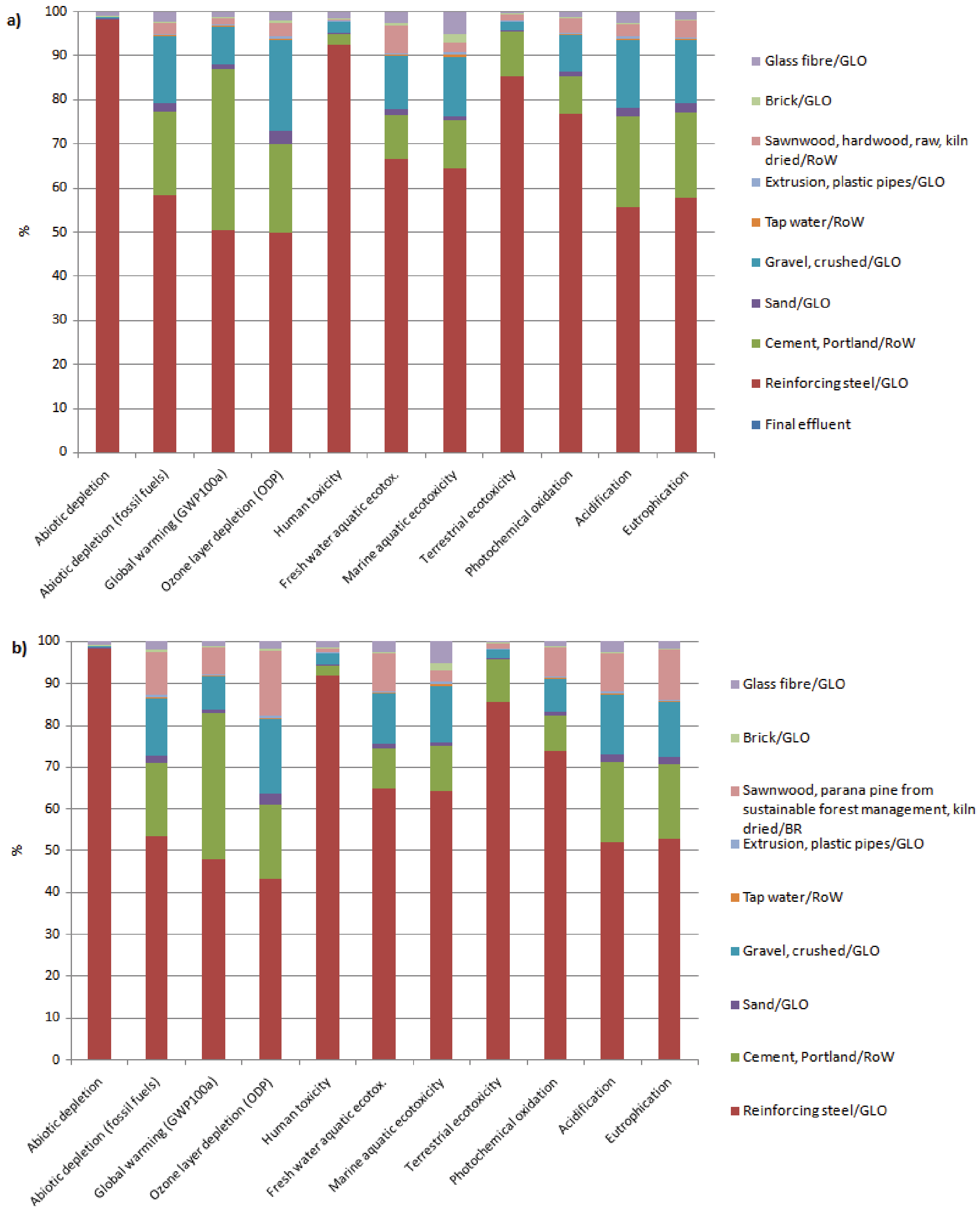

Fig. 2. Contribution of each sawnwood background process to the overall environmental impacts (WWTP construction phase). (a) sawnwood, hard wood, raw, kiln dried/RoW and (b) sawnwood and parana pine from sustainable forest management/BR.

The results shown in Fig. 2 illustrate a remarkable difference between the impact potential obtained using the sawnwood and parana pine from sustainable forest management/BR background processes (Fig. 2b) and those resulting from the choice of RoW background processes, except for the Terrestrial ecotoxicity category. The characterization factors of the two analyzed sawnwood background processes available in the Ecoinvent© database also varied greatly depending on the impact category. The results are summarised in Table 3.

The sawnwood, parana pine/BR background process would be the most appropriate process for the present study, since it is expected to have greater geographic and technical representativeness. Besides, this process indicates a

Table 2
Life cycle inventory of a WWTP

WWTP with disinfection			
Inputs			Source
Reinforcing steel/GLO	0.055	kg m^{-3}	WWTP project
Cement, Portland/RoW	0.078	kg m^{-3}	
Sand/GLO	0.248	kg m^{-3}	
Gravel, crushed/GLO	1.479	kg m^{-3}	
Tap water/RoW	0.053	kg m^{-3}	
Extrusion, plastic pipes/GLO	0.002	kg m^{-3}	
Sawnwood, hardwood, raw, kiln dried/RoW	0.001	m^3 m^{-3}	
Brick/GLO	0.003	kg m^{-3}	
Glass fibre/GLO	0.001	kg m^{-3}	
Electricity, medium voltage/BR	0.180	kWh m^{-3}	WWTP Operation
Gravel, crushed/GLO	0.925	kg m^{-3}	
Sodium hypochlorite, without water, in 15% solution/GLO	0.030	kg m^{-3}	
Air emissions			
Methane, biogenic	0.343	kg m^{-3}	[12]
Dinitrogen monoxide	0.001	kg m^{-3}	[13]
Final waste			
Waste, final, inert	0.925	kg m^{-3}	Operation
Water emissions			
BOD_5, Biological oxygen demand	0.021	kg m^{-3}	Laboratory analysis
COD, Chemical oxygen demand	0.096	kg m^{-3}	
Suspended solids, unspecified	0.018	kg m^{-3}	
Ammonia, as N	0.039	kg m^{-3}	
Nitrogen, total	0.046	kg m^{-3}	
Nitrate	0.002	kg m^{-3}	
Phosphorus, total	0.008	kg m^{-3}	
Free chlorine	0.001	kg m^{-3}	Operation

sustainable forest management system, which is expected to contribute less to global environmental impacts. However, this process presents greater impact potential for all categories, except for terrestrial ecotoxicity (Fig. 2b).

According to the original inventory of the sawnwood/BR background process, available in the Ecoinvent© database, the high impact potential came from log transportation between South America and Europe. Transport takes place via large ships with high consumption of diesel oil, resulting in large emissions of greenhouse gases. Moreover, the modeling and calculations consider that the fuel (petrol low-sulfur), is totally converted into non-methane volatile organic compounds (NMVOC). This explains the high impact of this background process, mainly in the abiotic depletion, global warming, and ozone layer depletion categories.

Obviously, the impact from transportation cannot be accounted for as a contribution to the environmental impact potential, when the use of sawnwood occurs within Brazil. It is evident that the sawnwood, parana pine/BR background process overestimates the potential environmental impact of the use of this material in Brazil. The sensitivity analysis demonstrates that, depending on the background process chosen in the Ecoinvent© database, the results of the impact assessment will be significantly different, and this interferes in the interpretation of the study, with regard to the potential environmental impact. Therefore, the choice of background process in the database can be crucial to the reliability of the LCIA.

These results agree with others previously published in the scientific literature. Gallego-Schmid and Tarpani [7] highlighted that the databases focused on Europe and North America, and needed to be adapted for use in developing countries, due to a need for more site-specific databases. In addition, the LCA studies applied to WWTP in developing countries need more affordable access to background databases and increased access to current LCA software.

The presentation of a detailed LCI which specifies the background processes used from the Ecoinvent© database, is an important requirement for LCA studies, in order to provide an accurate interpretation and adequate assessment. The background process brings its production chain and services and these impacts are accounted for in the LCIA results and must be discussed during their interpretation.

Table 3
Characterization factors of sawnwood background processes available in the Ecoinvent© database

Categories	Sawnwood, hardwood, raw, kiln dried/RoW	Sawnwood, parana pine from sustainable forest management, kiln dried/BR	Difference
Abiotic depletion, kg Sb eq	1.21E-10	3.64E-10	200%
Abiotic depletion (fossil fuels), MJ	4.30E-02	2.14E-01	398%
Global warming (GWP100a), kg CO_2 eq	3.24E-03	1.65E-02	409%
Ozone layer depletion (ODP), kg CFC-11 eq	3.95E-10	2.27E-09	474%
Human toxicity, kg 1.4-DB eq	6.09E-04	1.67E-03	175%
Fresh water aquatic ecotoxicity, kg 1.4-DB eq	1.01E-04	1.47E-04	46%
Marine aquatic ecotoxicity, kg 1.4-DB eq	1.24E+00	1.54E+00	24%
Terrestrial ecotoxicity, kg 1.4-DB eq	1.46E-05	1.28E-05	-12%
Photochemical oxidation, kg C_2H_4 eq	3.12E-06	6.46E-06	107%
Acidification, kg SO_2 eq	2.46E-05	9.38E-05	281%
Eutrophication, kg PO_4 eq	4.51E-06	1.58E-05	252%

Some authors stated that the impact of the construction phase is negligible in the context of the entire WWTP life cycle [16,17]. However, the poor quality of LCI cannot be neglected. Data from materials and infrastructure obtained with high levels of uncertainty may underestimate the potential impacts of the construction phase on the LCA results. This reinforces the great importance of a regionalized database and the need for a detailed LCI that would provide data sources and background data to allow a more careful evaluation of the results and, consequently, increased reliability, and reproducibility.

In order to investigate the validity of the hypothesis, another sensitivity analysis, using similar background processes available in different databases, was performed. Fig. 3 shows the results of using two apparently similar background processes: "extrusion, plastic pipes" and "PVC pipe E." In this case, it is important to note that the "PVC pipe E" background process belongs to the Industry 2.0 database and "extrusion, plastic pipe" to the Ecoinvent© database.

Considering all of the environmental impact categories, the impact potential shows a large variation (0.9%–54.0%) for the "PCV pipe E" background process (Fig. 3b). On the other hand, the environmental impact potential for the "Extrusion, plastic pipes" background process presents a small variation (0.02%–0.75%). The difference between these two processes is evident and remarkable, requiring a careful investigation of the contribution of PVC pipe E on the potential environmental impacts for the WWTP construction phase. Regarding the reliability of the studies, the hypothesis that the choice of processes can result in major misinterpretations and overestimation of the potential environmental impacts is confirmed.

The inventory contribution network for the freshwater aquatic ecotoxicity category was generated by the SimaPro© software and can be seen in Fig. 4. In order to know the chain of processes involved in the production of PVC pipe E, this category was chosen because it presents the greatest environmental impact potential. The method considers some emissions of Dioxin, 2, 3, 7, 8, tetrachloride dibenzo to the water, due to the transportation of the PVC pipe E. However, the environmental compartment most affected by the emission of these pollutants is the atmosphere, which may be an inconsistency. Therefore, in practical terms, the choice of the PVC pipe E background process is not the most appropriate, in this study. The choice of the Extrusion, plastic pipes background process from the Ecoinvent© database is the best option, taking into account the distribution of impacts in all categories.

It should be pointed out that, for the application of the LCA, it is necessary to discuss what was accounted for in the background processes from the databases and not only the graphs resulting from the LCIA. A starting point is to investigate the databases' inventories in a deeper way.

Another important result from sensitivity analysis is that using processes from different databases increases the uncertainty of the study. Different databases use different methodologies for calculating the indicators of the specific impact categories. The investigation of the numerical and methodological differences in databases applied to LCA and the results showed that the numerical differences are remarkable in some points. In most cases, they originated from multiple data sources, indicating the importance of obtaining consistent data and a clear statement of the basis for a comparative assessment [18].

3.2. Analysis of the electricity background process

Many studies in Europe have concluded that the greatest potential impact of the WWTP is that regarding energy consumption during the operation phase [11,15,19]. Therefore, the contribution of electricity medium voltage/RoW and electricity medium voltage/BR background processes, available in the Ecoinvent© database, were evaluated. The results are shown in Fig. 5.

The contribution of the potential impacts of electricity, medium voltage/BR and electricity, medium voltage/RoW process to the WWTP operation phase varied depending on the impact category (Fig. 5). The differences from one process to another are remarkable. The impact potential of electricity/RoW is more than double that of the potential impact of electricity/BR, in most categories. It is necessary to point out that the inventory for the Brazilian energy

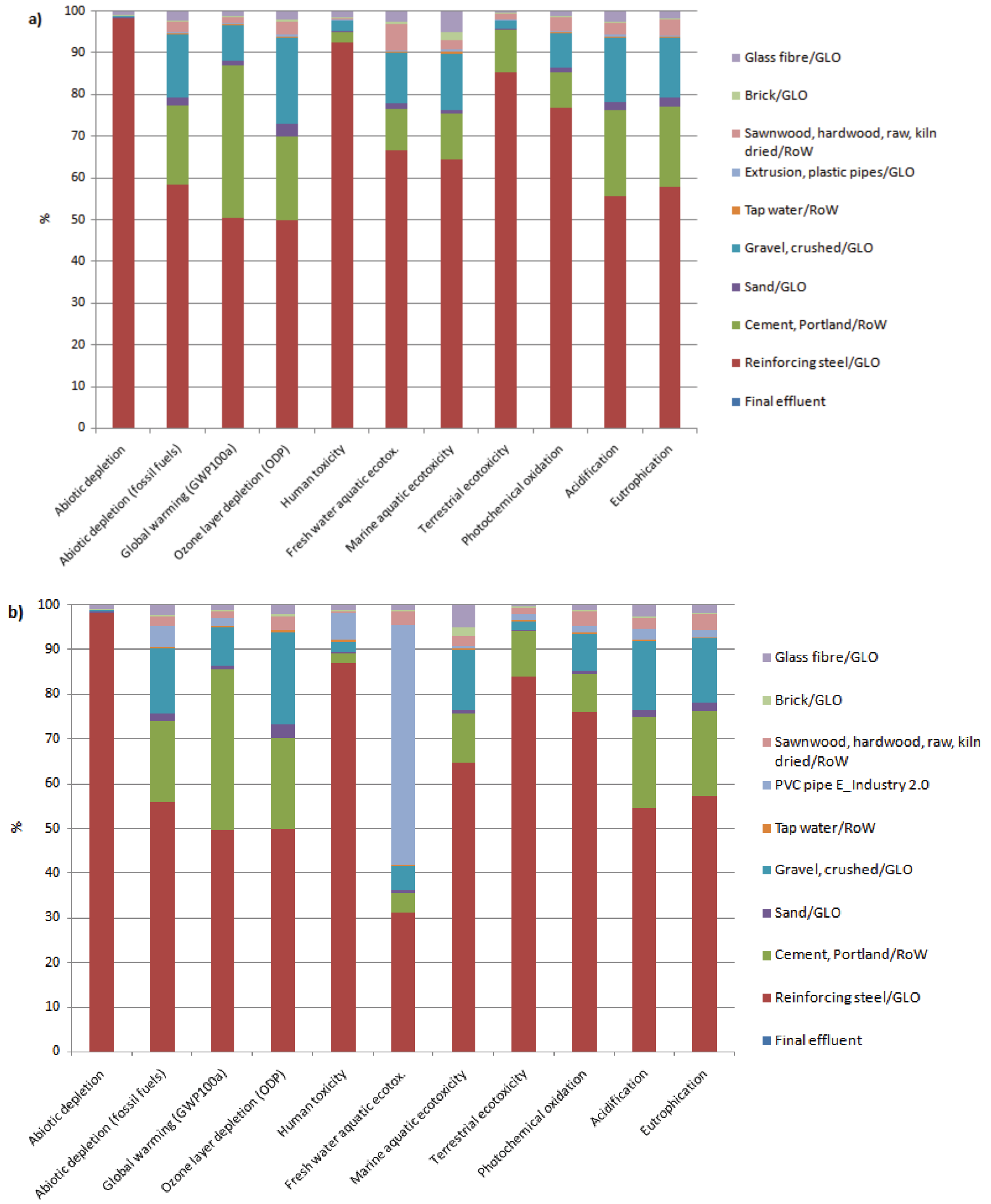

Fig. 3. Contribution of "PVC pipe E" and "Extrusion, plastic pipes" background processes to the overall environmental impacts for WWTP construction phase. (a) Extrusion, plastic pipes/GLO and (b) PVC pipe E.

matrix is in accordance with the data published by the National Energy Balance Initiative, with predominantly hydroelectric power plants. The electricity/RoW represents the rest of the world geographical data set for electricity production, which actually has the greatest environmental potential impact, once European countries present their energy matrix, based on fossil sources. The results show that the country-specific choice of the mix of the electricity background process is crucial for adequate interpretation by decision-makers.

Although some authors show an extensive inventory in published papers, the LCI does not describe the

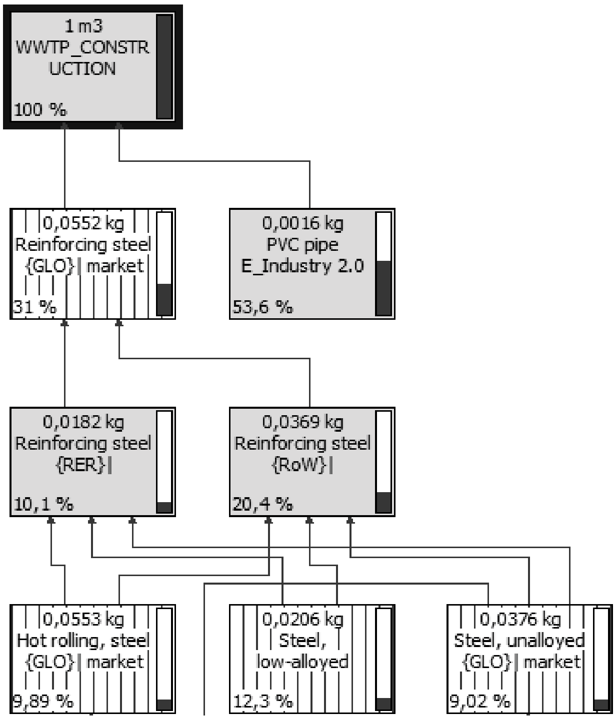

Fig. 4. Contribution network for the freshwater aquatic ecotoxicity category.

background data and its source in detail, which does not allow reproducibility or comparison with similar studies [2,4,5]. A detailed LCI, identifying the sources and specifying the background process in the database, is important to improving the reliability of results and to promote the correct interpretation of environmental impacts. The LCA proposes to identify the chain of impacts of a product or a system and not only the point effect. Therefore, it is necessary to know the input and output flows of the systems, in order to reach conclusions about the potential impacts of the WWTP studied.

The absence of reliable databases in the sanitation sector in developing countries is an important gap. The majority of the existing databases have different objectives and approaches. There is no well-defined period of data collection and there is usually a lack of validation tools, regarding the information provided. The systematization and transparency of the data would enable the development and effective monitoring of the sanitation sector. Therefore, it is necessary to invest in the reliability of the information in the sanitation sector for the construction of knowledge, in order to improve public policies in this sector, mainly in developing countries such as Brazil, Mexico, India, and South Africa.

In addition, it is necessary to invest in databases of the production of raw materials and capital goods in these countries. Extraction of natural resources, production of capital goods and the energy matrix are peculiar in these regions of the planet and the use of data obtained on the European continent, USA, or Canada may lead to a misinterpretation of the results.

Such efforts are being made, specifically in Brazil. The Brazilian Institute of Information in Science and Technology (IBICT) created the Brazilian inventory database (SICV) and is working on the data quality guidelines (QualiData) for data submission [20,21]. The objective is to support the execution of research projects, focused on the construction of LCI that will feed the National life cycle inventories Bank (SICV Brasil) with inventories that are representative of the Brazilian economy.

Therefore, to increase the consistency and reliability of LCA studies applied to WWTP it is important to spend time and resources on collecting representative and reliable data. The LCI will be more transparent if the data is presented with the sources and specifications of the background processes used in the databases. It is important to emphasize that the appropriation of the object of study is of great relevance for the users to make the most appropriate choices. The LCA studies applied to WWTP to support decision-making should present a detailed LCI because of the great importance to public health, social, and environmental interest.

International funding organizations, such as the World Bank, are demanding detailed studies on environmental gains and losses before the elaboration of projects and the release of financial resources to improve sanitary conditions in developing countries. LCA could be a good option to demonstrate the potential environmental impacts of structures such as water or WWTPs. However, to ensure maximum reliability of these studies, some recommendations must be followed. Table 4 shows crucial points listed from the results of the sensitivity analyses conducted with the LCI data and some recommendations for overcoming them.

Therefore, the application of LCA in the wastewater treatment sector still needs improvement regarding data quality, reproducibility, and transparency. However, these LCA studies allow us to identify the potential environmental impacts that go beyond the protection of watercourses and human health, to include environmental performance in the construction and operation of the WWTP, as a preventive action toward sustainability.

4. Conclusions

Despite the large number of LCA studies published and applied to WWTP, few allow the reproducibility of the results, due to a lack of inventories and data transparency, which requires a detailed LCI. The lack of an LCI in the studies does not permit the validation of their results because it is not possible to verify the data quality and transparency.

With the aim of improving the credibility of LCA studies in WWTP, the presentation of a detailed LCI becomes essential, as it allows the reviewers to scrutinize all of the data. The inability to verify the data or lack of consensus among similar studies makes it impossible for the LCA study to be used as a relevant tool for decision-makers.

The choice of background processes in the databases requires the attention of experts. Otherwise, the results can overestimate impact potentials. The comparison between background processes should be done in rounds of LCIA in the software tool before completing the LCI. The inventories from databases must be investigated in order to know what

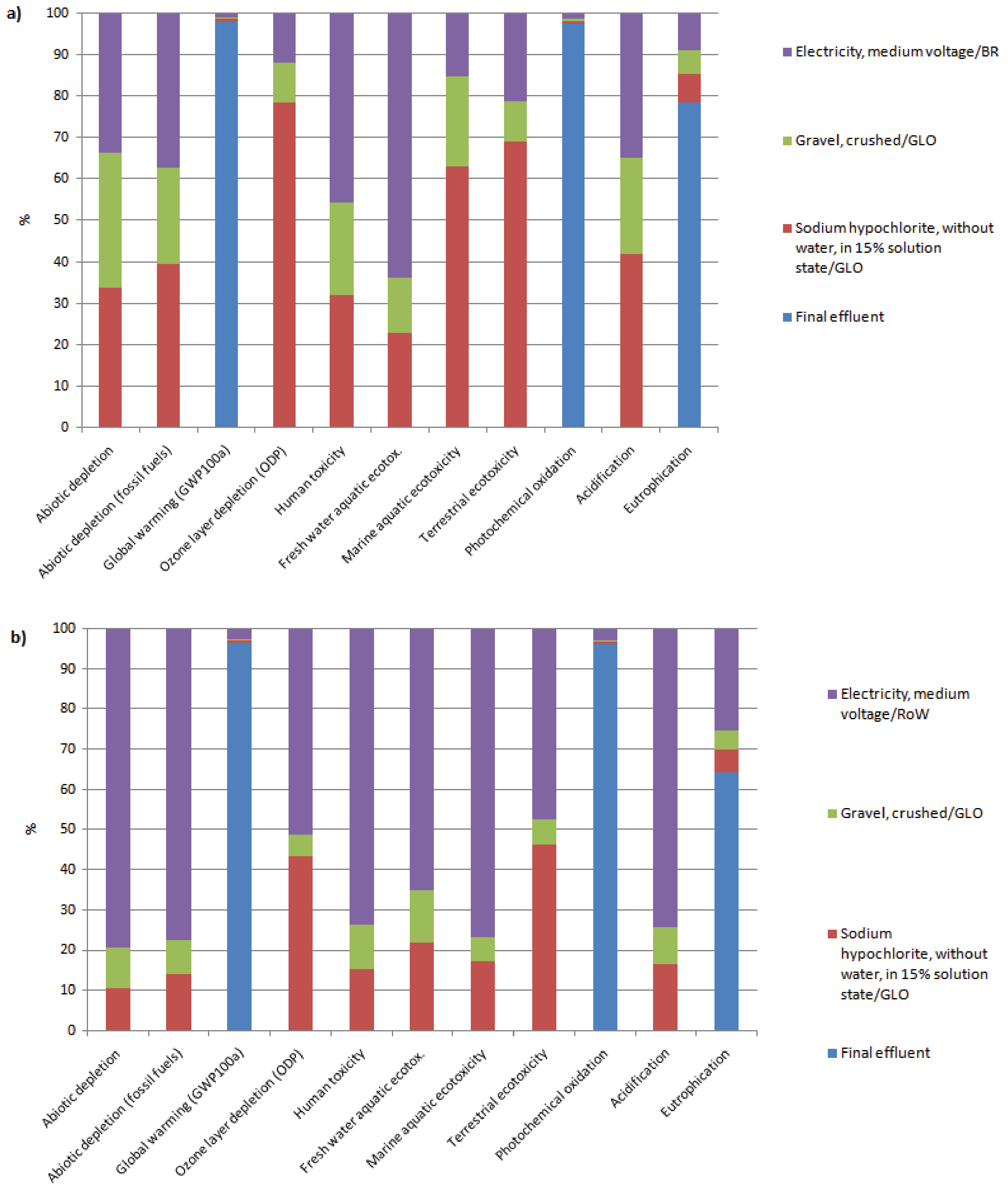

Fig. 5. Contribution of electricity, medium voltage/BR, and electricity, medium voltage/RoW background processes for the WWTP operation phase. (a) Electricity medium voltage/BR and (b) electricity medium voltage/RoW.

is being accounted for and then evaluated to check if the presented results are adequate for the study.

Therefore, the choice of background processes available in databases should be judicious and analyzed for their potential impact, considering the objectives, and boundaries of the study. In addition, LCIA results should be further discussed, questioning whether the results presented are consistent with the local reality.

LCA studies applied to WWTP to support decision-making should present a detailed LCI in the light of the relevance to the public, social, and environmental health of the wastewater treatment systems.

Table 4
Main limitations and recommendations for detailed LCI

Crucial points	Recommendations
Lack of data transparency	Present detailed LCI with the source of the information
LCA studies applied to WWTP without detailed LCI	Present the LCI as a table with the input and output flows in detail and provide source
LCI without specification of the background processes used	Specify the background processes used from the database
Choice of background processes in databases	Analyze the contribution of the impacts of similar background processes available in a database
	Evaluate the contribution network of impacts to the background process used
	Investigate, in depth, the inventories available in the databases
Similar background processes available in databases	Discuss what was accounted for in the inventory of the background processes in databases
Use different databases	Sensitivity analysis should be applied, to compare the databases process
	Analyze the background process inventory
Lack of representativeness of studies	Strengthen local databases, especially in the sanitation sector

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