



Life cycle assessment of urban wastewater treatment plants: a critical analysis and guideline proposal

Thais Ayres Rebello, Regiane Pereira Roque, Ricardo Franci Gonçalves , João Luiz Calmon and Luciano Matos Queiroz

ABSTRACT

In its 30 years of existence, there are still many improvement possibilities in studies performing the life cycle assessment (LCA) of wastewater treatment plants (WWTPs). Hence, this paper aims to start a guideline development for LCA of urban WWTPs based on the information available in the scientific literature on the topic. The authors used the ProKnow-C systematic review methodology for paper selection and 111 studies were analyzed. The most significant points that can be improved are caused by missing essential information (e.g. functional unity and input data). Other important methodological aspects are covered: allocation process, functional unit choice, sensitivity analysis, and important fluxes to be considered. Many opportunities within the LCA of WWTPs were identified, such as optimization of WWTP operational aspects and resource recovery. Furthermore, LCA should be combined with other methodologies such as big data, data envelopment analysis, life cycle cost assessment, and social life cycle assessment. To achieve this potential, it is clear that the scientific and technical community needs to converge on a new protocol to ensure that LCA application becomes more reliable and transparent.

Key words | environmental impact assessment, guideline, life cycle analysis, ProKnow-C, urban wastewater, wastewater treatment

Thais Ayres Rebello (corresponding author)
Regiane Pereira Roque
Ricardo Franci Gonçalves 
João Luiz Calmon
Federal University of Espírito Santo, Vitória, Brazil
E-mail: rebello.ayres.thais@gmail.com

Luciano Matos Queiroz
Federal University of Bahia, Salvador, Brazil

HIGHLIGHTS

- One-hundred and eleven papers on life cycle assessment of wastewater treatment were analyzed.
- Less than a third of papers presented all information needed.
- The most common mistakes are lack of software indication and undefined scope.
- A guideline is proposed aiming to improve papers' overall quality and reliability.

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY-NC-ND 4.0), which permits copying and redistribution for non-commercial purposes with no derivatives, provided the original work is properly cited (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

doi: 10.2166/wst.2020.608

GRAPHICAL ABSTRACT



LIST OF ABBREVIATIONS

WWTP	Wastewater treatment plant
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
UASB	Upflow anaerobic sludge blanket
ISO	International Organization for Standardization
AnMBRs	Anaerobic membrane bioreactors

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 also create environmental impacts (Mo & Zhang 2013; Lee *et al.* 2017). Hence, they should be assessed carefully considering the inputs and outputs fluxes of the life cycle phases, evaluating its environmental performance as a whole system. To do this, many authors opt for the life cycle assessment (LCA) methodology.

The LCA methodology is a comprehensive, analytical tool that evaluates the environmental impact of a product or system throughout its entire life cycle (Vieira *et al.* 2016). Baitz *et al.* (2013) argue that the LCA is a recognized trustworthy tool that conducts scientific and intelligible results to assess the environmental sustainability of human activity. Zang *et al.* (2015) highlight that the LCA power is contained in the boundary expansion to comprise all impacts upon the environment, which helps to avoid transferring burdens to another production stage.

The rigorous application of LCA in WWTPs occurred for the first time in the 1990s, in an attempt to assess environmental gains at these facilities. The methodology proved to be valuable in pointing out the environmental

impacts associated with the WWTP project and operation. Since then, the growing interest on the part of researchers and professionals in the use of LCA in the area has resulted in the publication of extensive literature, making it necessary to review the advances and challenges encountered.

Some review papers regarding the Life Cycle Assessment of WWTPs are available (Mo & Zhang 2013; Zang *et al.* 2015; Hwang *et al.* 2016; Heimersson *et al.* 2016; Sabeen *et al.* 2018; Sena & Hicks 2018; Gallego-Schmid & Tarpani 2019). Most of those papers, however, do not follow a systematic revision method. Additionally, these studies cover the main results assessed by the original papers analyzed and some of those review papers focus on specific types of systems.

Corominas *et al.* (2013) published a comprehensive review paper about LCA applied to WWTPs up to 2013. The authors evaluated the methodological steps carried out on 45 papers. They concluded that stricter adherence to ISO (International Organization for Standardization) methodological standards is needed to ensure transparency and quality of results. The authors found that the LCA challenge is increased with the new paradigm of WWTPs, now perceived not only as pollution control equipment but also as a resource recovery facility. Moreover, all 45 papers had stated both the scope and goal of the work and 60% of the articles used as a functional unit the volume of treated wastewater, and 42% of the studies did not show which life cycle impact assessment (LCIA) methodology was used.

To date, no specific ISO norm is available for WWTPs, such as the ISO 13315-1:2012 and ISO 13315-2:2014 that provide specific guidelines for concrete structures. Additionally, either existing frameworks are based on specific systems, such as activated sludge systems, or do not cover the basic structure of an LCA study. Due to this lack of information, many papers lack some needed information or cannot be compared due to the differences in the frameworks chosen.

This work aims to propose a guideline framework based on the shortcomings and good practices identified in the literature reviewed. The paper also aims to show the advancements, main gaps, and opportunities for future development within this scientific area. Even though the LCA can be applied to assess the environmental performance of WWTPs, the guideline proposal is justified by improving the reliability, transparency, and accuracy of the LCA studies. Essentially, an LCA study is subjective, as the analyst, for example, chooses the goals and boundaries of the system. Therefore, guidelines certainly will help to overcome some important bottlenecks found in this field, such as choice of the background processes in databases, the allocation of environmental burdens in resource recovery WWTP, representative functional unit, and sensitivity analysis parameters and methods.

METHODOLOGY

Systematic review methodology

A guideline proposal requires careful literature review to understand the most significant shortcomings in previous works that can be improved in future research. The best practices should be highlighted, to summarize the

knowledge available. To ensure results would not be misleading (without subjective bias), and representative of the best articles available, authors conducted a systematic review using the ProKnow-C method.

The ProKnow-C, Knowledge Development Process and Constructivist method, developed by [Ensslin *et al.* \(2010\)](#), consists of four main stages: (1) document selection; (2) bibliometric analysis; (3) systematic analysis and; (4) identification of literature gaps.

In the first step, the Scopus database was chosen due to the number of journals, websites, patents, and available documents it contains ([Ferenhof *et al.* 2014](#)). The key-words applied were ‘wastewater treatment’ and ‘life cycle assessment’ or ‘LCA’, since they resulted in the highest number of relevant materials.

After that, the authors filtered papers to secure their relevance in the field. The filters used were ‘article’ and ‘review’ from 2013 until 2019 to complement the literature overview previously published by [Corominas *et al.* \(2013\)](#). Only journals evaluated with a Q1 quartile classification on the Scientific Journal Rankings were considered.

The systematic methodology was followed by abstract reading and filtering papers according to the wastewater type desired (urban sewage). Papers that only mentioned the LCA methodology but not its application were excluded from the analysis ([Figure 1](#)). To improve this work

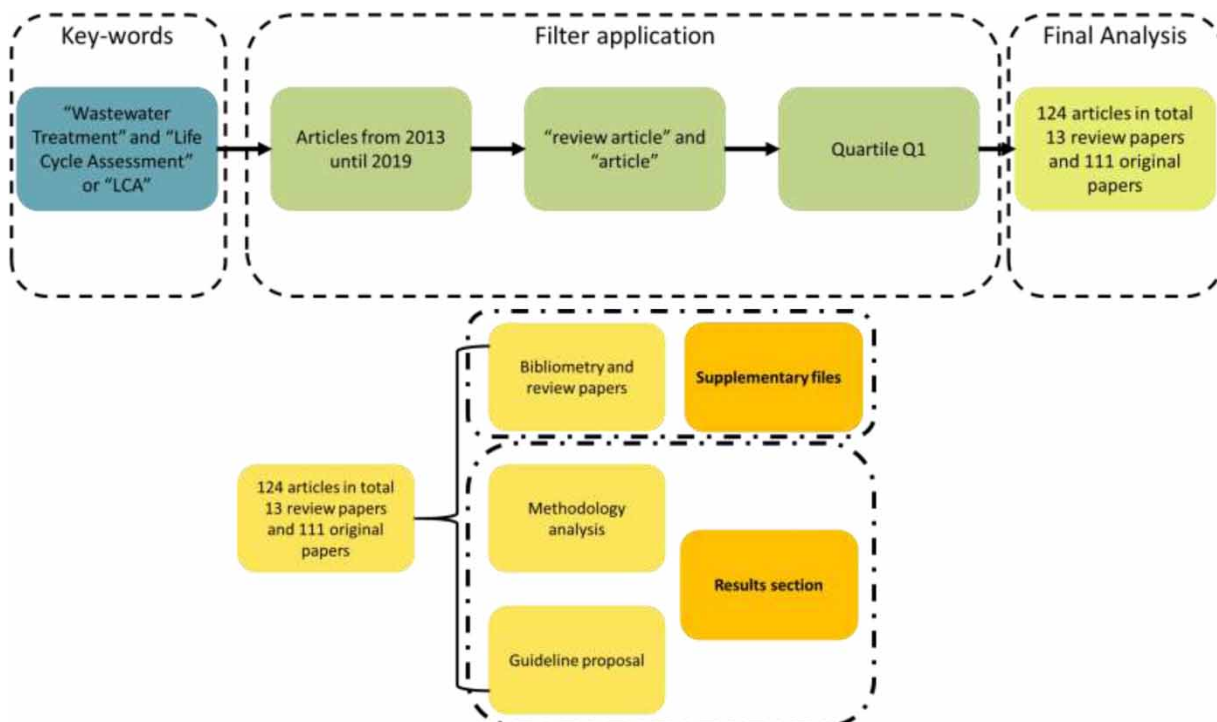


Figure 1 | Methodology used for paper selection.

discussion and methodology, the authors used other documents such as articles, dissertations, and books as support. However, only the 124 papers selected (13 reviews and 111 original papers) were analyzed.

The bibliometric analysis covered: (1) Year of Publication; (2) Publications by Journals; (3) Country and; (4) Institution of the first author. Since the LCA can be carried in a different location to that of the data generated or the WWTP itself, the first author location was used. Previous literature reviews were also analyzed to see if the authors have suggested good practices for this literature field. To see the bibliometric analysis disclosed results please refer to the Supplementary Materials.

Papers' methodology analysis

The 111 original articles were analyzed by how the LCA methodology was applied. Authors used ISO 14040:2006 and ISO 14044:2006 as a baseline to judge studies and help to construct the final guideline. ISO 14040:2006 comprises the description and framework of LCA studies including goal and scope definition, life cycle inventory analysis, LCIA, and interpretation phase. ISO 14044:2006 specifies requirements and guidelines for LCA including all methodological phases. Both ISO standards do not address LCA of urban WTP in particular. While it is advantageous for authors to follow them, they also allow space for assumptions to complete the study. Thus, by not defining the details of the LCA application, studies may lead to inconsistencies making their comparison rather difficult.

A proper scope definition is the one that stated the systems analyzed, functional unit, and the system boundary. The type of data (background or foreground) and the database were used as criteria to assess the life cycle inventory (LCI) phase. In the LCIA phase, the authors analyzed the software used, the LCIA methodology, if the study used the midpoint or endpoint approach, and the midpoint categories evaluated.

In the end, a guideline is proposed, based on common shortcomings and the good practices identified. The analysis also included the significant contributors for eutrophication, climate change, acidification, and toxicity in WWTPs to understand what can be performed to minimize uncertainties in these environmental indicators.

METHODOLOGY ANALYSIS

Goal and scope definition

From the 111 articles that applied the LCA methodology, 100% stated clearly the study goal. Comparative analysis

accounted for 71.67%, while 7.50% analyzed the environmental impact of one system. Around 8.33% of the studies analyzed the environmental performance of urban water systems (Amores *et al.* 2013; Lemos *et al.* 2013; Lane *et al.* 2015; Risch *et al.* 2015; Loubet *et al.* 2016; Pintilie *et al.* 2016) and 2.50% aimed to optimize the wastewater treatment (Bisinella de Faria *et al.* 2015; Xiong *et al.* 2018). Apart from these, Morera *et al.* (2015) analyzed the environmental impact of combining two neighboring systems.

Only 75.68% of the works clearly defined the scope of the paper. From the 24.32% that did not, 85.19% omitted a clear definition of the WWTP type; 11.11%, the functional unit; 29.63%, the inclusion of the sludge line; and 11.11% did not indicate which phases were included in the analysis (construction, operation, maintenance and/or destruction phase).

Around 66% of the reviewed articles used volume as a functional unit, of either treated wastewater (26.67%), potable water (1.67%), or untreated wastewater (31.67%). Up to 5% of the papers used population equivalent load (Risch *et al.* 2014; Papa *et al.* 2016; Lutterbeck *et al.* 2017; Malila *et al.* 2019). Some studies used time-related functional units, such as wastewater treatment in the last 28 days (Lu *et al.* 2017) and the impact of a five-people system in 1 year (Lehtoranta *et al.* 2014). The recovery of materials was also used, e.g., nitrogen (Diaz-Elsayed *et al.* 2017), phosphate (Longo *et al.* 2017), and biofuel (Lin *et al.* 2016; Shuai *et al.* 2016), which may indicate a shift on WWTP perception: not only as a treatment facility but also as a recovery facility.

Regarding the boundaries adopted on the LCA works, most papers have only considered the operational phase, and over 80% considered the sludge treatment line in the work (Figure 2). From the papers considering the construction and the operational phases, 21% evaluated activated sludge systems, 17% considered constructed wetland systems,

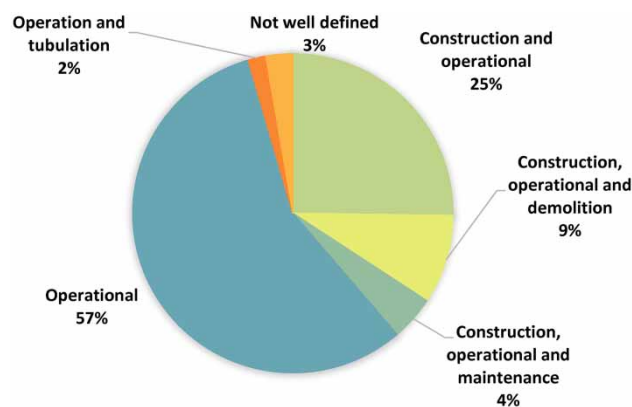


Figure 2 | Boundaries used in the LCA studies.

and only 10% considered anaerobic systems. Regarding the demolition phase, 20% of the works evaluated activated sludge systems and 20% evaluated anaerobic membrane bioreactors (AnMBRs). From those considering the maintenance phase, 40% were evaluations of activated sludge systems, and 40% from anaerobic systems.

According to Earles & Halog (2011), consequential LCA is used to describe how flows can change as a consequence of demand variations, and the processes that are immediate to the product system boundaries are relevant to the study. To perform a consequential LCA, economic data is used to measure how the operation's physical flows are affected. The attributional LCA, on another hand, measures immediate physical flows (resources, material, energy, and emissions) and usually applies the average data for each unit process. It was observed that most studies did not state if the analysis was conducted as an attributional LCA or a consequential study, which is a problem identified not only in WWTP evaluations (Weidema *et al.* 2018).

Life cycle inventory analysis

Corominas *et al.* (2013) observed the need for enhancements in data availability and data quality in LCA studies. After 7 years, the same needs were observed. From the 111 papers selected, 7.21% did not show the LCI data. Around 50% of papers used a combination of foreground and background data from literature and databases, 19.17% used foreground, and 19.17% used background data. Five papers did not state clearly the data source. It is important to understand that background data and estimations could not be representative of the specific reality of the scope and goal of the papers, but an analysis of whether to choose background, foreground or both should be made using specific criteria (such as data quality matrices).

Most of the studies used Ecoinvent[®] or Gabi[®] as the database. The use of local databases such as the Korean Ministry of Environment database (Piao *et al.* 2016) and the European Life Cycle Reference Database (Niero *et al.* 2014), which may lead to fewer uncertainties in the analysis, was also identified. The LIPASTO[®] database, a specific traffic database, was recognized in Lehtoranta *et al.* (2014).

Life cycle impact assessment and interpretation

From the 111 articles, 40.45% did not state which software was used, 33.33% used the SimaPro[®] software, 15.32% used Gabi[®], 3.60% OpenLCA[®], and 1.80% used Umberto[®]. Other software used were JEMAI-Pro 2.1.2

(Limphitakphong *et al.* 2016), Daycent (Miller-Robbie *et al.* 2017), Easetech (Fang *et al.* 2016), WaLA implemented in Simulink/Matlab (Loubet *et al.* 2016), and Wastewater-Energy Sustainability Tool (Holloway *et al.* 2016). Only 45.05% of the studies stated the version of the software, which can influence deeply the results found, especially for software that includes directly the database and the methodology assessment methods, such as SimaPro[®]. Figure 3 shows the most significant LCIA methodologies used in the LCA of WWTP studies.

There is considerable growth in the use of the ReCiPe methodology when compared to Corominas *et al.* (2013) findings, which included one work published with this method. The ReCiPe is a new method, first developed in 2008, created by the inventor of CML 2001 and Ecoindicator 99 and it is a fusion of both methodologies. It contains 18 midpoint indicators and 3 endpoint indicators, and depending on which software interface the operators use, it calculates indicators at the same time.

Exactly 84.68% of the studies used midpoint categories, 3.60% endpoint, 11.71% used both, and one did not state the type of analysis. Nearly 77% of the articles used the eutrophication midpoint category. Other important categories were: global warming potential, present in 89.19% of the articles, acidification (64.86%), and toxicity (58.56%).

Only 27.03% of the studies applied a sensitivity analysis and 10.81% applied an uncertainty evaluation, which is very important in the construction of the LCA study since data availability is still a current problem in the field.

Most significant methodology aspects

We reinforce the need to provide basic information from articles, especially those that consider multiple systems. Figure 4 shows the most significant points analyzed. The

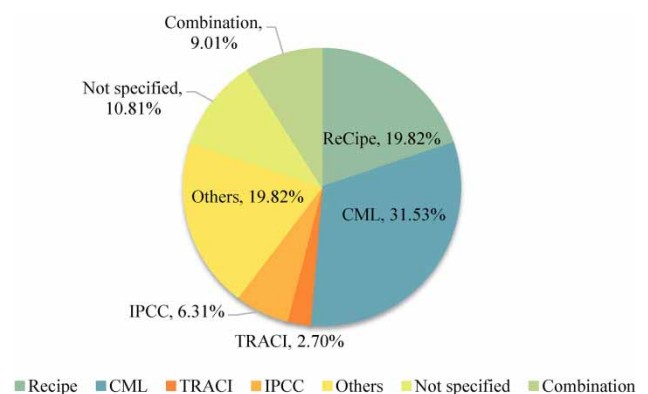


Figure 3 | Life cycle impact assessment methodologies used in the wastewater treatment plants.

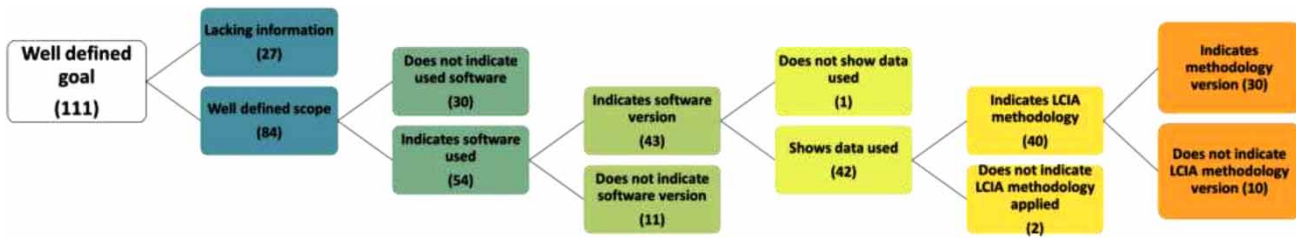


Figure 4 | Significant points analyzed during the research.

main drawbacks identified were: lack of information in the scope definition, LCI, and LCIA. Lack of sensitivity or uncertainty analysis, allocation in resource recovery systems, functional unit definition, and data quality and availability were also present. In conclusion, less than a third of papers (27%) were considered replicable.

This work identified the need to increase the transparency of studies and comparability. The analysis demonstrated the importance of a guideline or protocol to conduct LCA of WWTPs and the following sections aim to provide some suggestions for the main shortcomings identified.

Guideline proposal

Figure 5 shows the guideline proposal outline, derived from the most important shortcomings and good practices identified. The authors’ intention with this proposal is to help to develop the LCA of the urban WWTP field and initiate a debate towards a final standard or protocol.

Goal and scope definition

Comparative goals are encouraged since data quality and availability are the most significant difficulty within the LCA of WWTPs. There is also a need to provide a comparable functional unit that is representative and to include the important phases of each life cycle system if different types of systems are analyzed. This work recommends the use of 1 m³ of untreated wastewater as the functional unit since it can be used in all types of systems, regardless of resource recovery. Moreover, studies will not need to consider the losses and gains in the system to calculate each parameter, as they would when considering the volume of treated water. The functional unit should be accompanied by water quality basic information (chemical oxygen demand, turbidity, biochemical oxygen demand, pH, and others), to ensure the comparison between different papers is possible. Systems with source-separation of wastewater types should aim to: either adapt this functional unit, or use people equivalent, making sure the

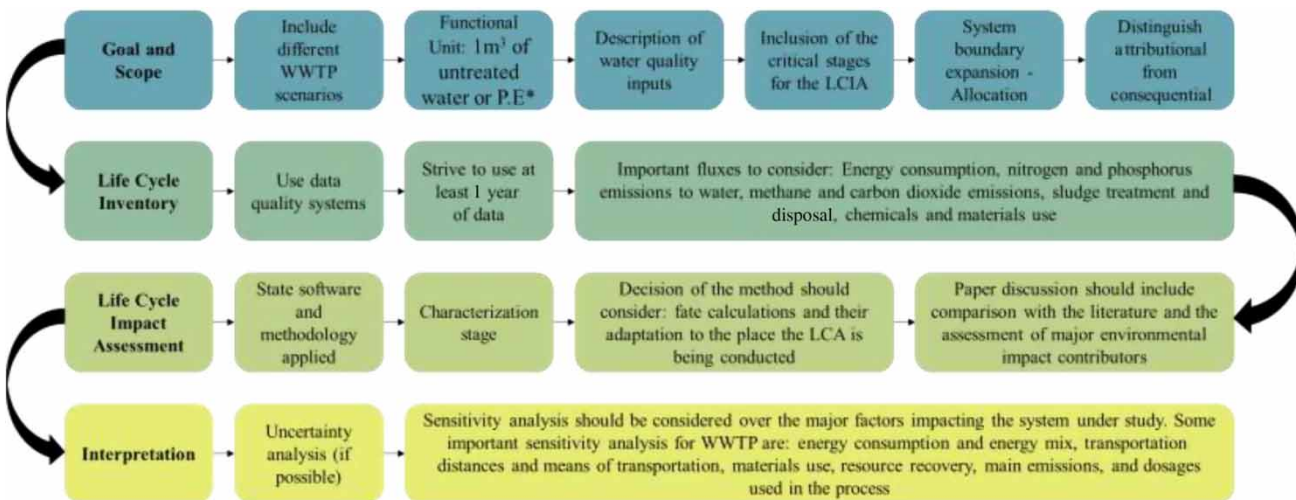


Figure 5 | Guideline outlines. *P.E: population equivalent.

parameters are established in the work. If assessing urban water systems (water capture, treatment, distribution, use, treatment, and disposal or recovery) authors could either use 1 m³ of potable water at the point of distribution, or population served.

If comparing different types of systems, studies should add the important aspects that differentiate them and could highly affect the environmental impact in the boundaries of the research. For instance, if the analysis focuses on systems with different efficiencies, water discharge should be included in the boundaries. Table 1 shows recommendations for each type of goal considered. System

boundaries must be as broad as possible and well indicated in the study, preferably in a diagram. Studies should clearly state if they present the results for the construction, operation, maintenance, and demolition phases, especially if data is condensed or the analysis was performed as one unique process. Natural systems such as wetlands, ponds, and upflow anaerobic sludge blanket (UASB) systems should consider the construction phase in the analysis when compared to different types of systems due to the representativeness of its environmental impacts (Table 2).

The literature presents incipient results regarding the importance of the maintenance and demolition phases and

Table 1 | Main goal recommendations, according to the types of goals identified in the literature

Goals	Recommendation	Reference
Comparison between wastewater treatment systems that do not present the same or equivalent efficiencies	Include water discharge and impacts to the water body	Miller-Robbie <i>et al.</i> (2017), Pretel <i>et al.</i> (2016)
Comparison between wastewater treatment systems that recover different types of product	For consequential LCA: use the substitution method. For attributional LCA: use comparative fluxes to avoid allocation	Brander & Wylie (2011), Muñoz <i>et al.</i> (2019)
Comparison between systems that reuse water and systems that do not reuse water	Include in the boundary water discharge for the system that does not reclaim water	Cornejo <i>et al.</i> (2013), Lane <i>et al.</i> (2015)
Analysis of one system	Include sensitivity analysis and/or Monte Carlo analysis ^a	Bai <i>et al.</i> (2019), Moretti <i>et al.</i> (2019)
Comparison between systems that do not produce the same amount of sludge or type of sludge	Include in the analysis the sludge treatment and disposal	Cashman <i>et al.</i> (2018), Lam <i>et al.</i> (2015)
Comparison between frugal systems (upflow anaerobic sludge blanket, constructed wetlands, ponds) and conventional systems	Include the construction phase in the boundaries	Arashiro <i>et al.</i> (2018), Garfí <i>et al.</i> (2017)

^aSensitivity or uncertainty analysis is encouraged for all goals; however, due to lack of data and information, studies that aim to assess the impact of only one system should mandatorily include at least one sensitivity analysis.

Table 2 | Important LCA stages to consider according to the literature review (over 10% impact in one environmental impact category)

Technology	Construction phase	Maintenance phase	Demolition phase
Activated sludge systems	Morera <i>et al.</i> (2017), De Feo & Ferrara (2017)	a	a
Membrane systems	Pretel <i>et al.</i> (2016), Holloway <i>et al.</i> (2016)	a	a
Upflow anaerobic sludge blankets	Lutterbeck <i>et al.</i> (2017)	a	a
Anaerobic systems	a	a	a
Anammox	a	a	a
Ponds	Hernández-Padilla <i>et al.</i> (2017)	a	a
Constructed wetlands	Lutterbeck <i>et al.</i> (2017), Lam <i>et al.</i> (2015)	a	a
Oxidation ditch	Hao <i>et al.</i> (2019)	a	Hao <i>et al.</i> (2019)
High rate aerobic pond	Arashiro <i>et al.</i> (2018), Garfí <i>et al.</i> (2017)	a	a
Soil biotechnology	Kamble <i>et al.</i> (2017)	a	a

^aNot enough data to conclude if the phase is relevant to be considered.

extra carefulness is needed with this data, which usually presents high uncertainties. Table 2 shows some suggestions of phase inclusion on different materials found in the literature (it was considered necessary to include if the life cycle phase represented more than 10% of an impact category). Regarding the construction phase, authors should always correlate the life-span of the facility aiming to improve the understanding of the technology and providing accurate data, especially if performing a comparison of different technologies that may present different life-spans. The inclusion of the operational phase should always be considered. Demolition, construction, and maintenance should be taken into consideration regarding results the literature has exposed and the goal of the work itself.

This study does not intend to set a specific type for wastewater treatment LCA since further research is needed on the topic. However, it is important to clarify what type of LCA is conducted, since this choice influences database use and allocation method selection.

Allocation is a delicate point of LCA studies and is used when the work presents more than one function. Hence, with resource scarcity and the evolution of WWTPs to the water-energy-food nexus concept, and resource recovery systems, the allocation is a new challenge studies must face. According to ISO 14040 and ISO 14044, both published in 2006, allocation should be avoided if possible. This is due to choices performed arbitrarily, such as mass, energy content, and economic value that allocate environmental burdens, which can lead to inaccuracies. There are two options to avoid allocation: subdivision of the system and expansion of the system. The subdivision consists of separating the stages that produce each of the functions on the system. However, according to Ekvall & Finnveden (2001) and Ekvall & Weidema (2004), this type of allocation avoidance methodology requires that the subsystems are divided either in time or space, and the authors argue that to use this type of consideration, the different products generated should be independent, and their quantities should not be affected by each other. Since this is hardly the case in WWTPs, the most accurate form to avoid allocation is the expansion of the system boundary technique: either subtracting the impact of the additional product, for consequential systems, or adding the impact of lacking products in the comparison scenarios, for attributional systems (Brander & Wylie 2011).

Life cycle inventory

The LCI is a delicate point in LCA studies, especially in developing countries that do not own a database adapted

to local reality. To improve the current situation, papers must provide all data inputted, especially for systems that are not present in the databases. For instance, in Ecoinvent 3.6, the new version of the most commonly used database, it is not possible to find a baseline process for UASB systems, wetlands, stabilization ponds, anaerobic sludge digesters, and AnMBRS. The development of databases for such technologies could represent a new branch of studies aiming to improve further future LCIA.

Since updates in databases may result in different environmental impacts, if selected, the authors stress the importance of stating which update and the version. Data precedence must be stated clearly, so its quality can be assessed. The assessment of the data quality is a requirement, since it may improve the understanding of data found, work limitations, and results, decreasing the uncertainty. The use of primary data is advisable, and it must be connected to the date it was obtained since the wastewater may alter throughout time. When performing an LCA using a database, the processes chosen and the adaptations performed to fit the goal and scope of the work should be stated.

If available, the best data quality should be used for all fluxes. However, usually, this is not the case. Hence, the effort to acquire the best quality data should be towards the fluxes that present the main impact contributions. The evaluation of the data quality can be accomplished by some methods, such as the Ecoinvent data quality assessment, and authors should use these methodologies to minimize the uncertainties of the results.

Concerning the unconventional results shown in Figures 6 and 7, energy could also be identified as an important eutrophication contributor due to nitrogen emissions during energy generation and distribution. This impacts mainly on marine eutrophication, especially on systems with a high nutrient removal efficiency, such as the submerged anaerobic membrane bioreactor. Toxicity environmental impacts are highly related to heavy metals from construction and energy. Wet-weather flows have an important impact on activated sludge systems due to the carrying of toxic compounds and the increase of energy use.

Although the LCA methodology has existed since the late 1960s, the data quality step is still not well developed. According to Edelen & Ingwersen (2018), data quality methods can be classified as semi-quantitative, such as the Ecoinvent and ILCD (International Reference Life Cycle Data System), and qualitative, such as the US Department of Agriculture method (binary qualitative pedigree matrix approach). Neither of these methodologies contains all the parameters asked by ISO 14044:2006. The most important parameters on the LCA of WWTP data quality are geographical, technological, and time-related

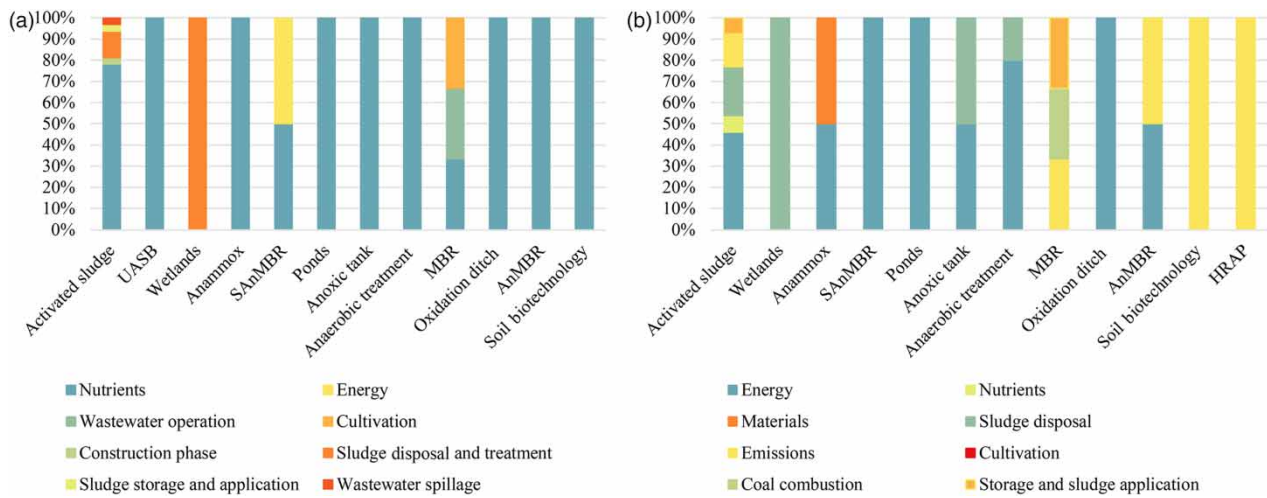


Figure 6 | Most significant processes for environmental impacts, as appointed by authors for (a) eutrophication and (b) acidification. UASB: upflow anaerobic sludge blanket, Anammox: anaerobic ammonium oxidation, SANMBR: submerged anaerobic membrane bioreactor, MBR: membrane bioreactor, AnMBR: anaerobic membrane bioreactor, HRAP: high rate algal pond.

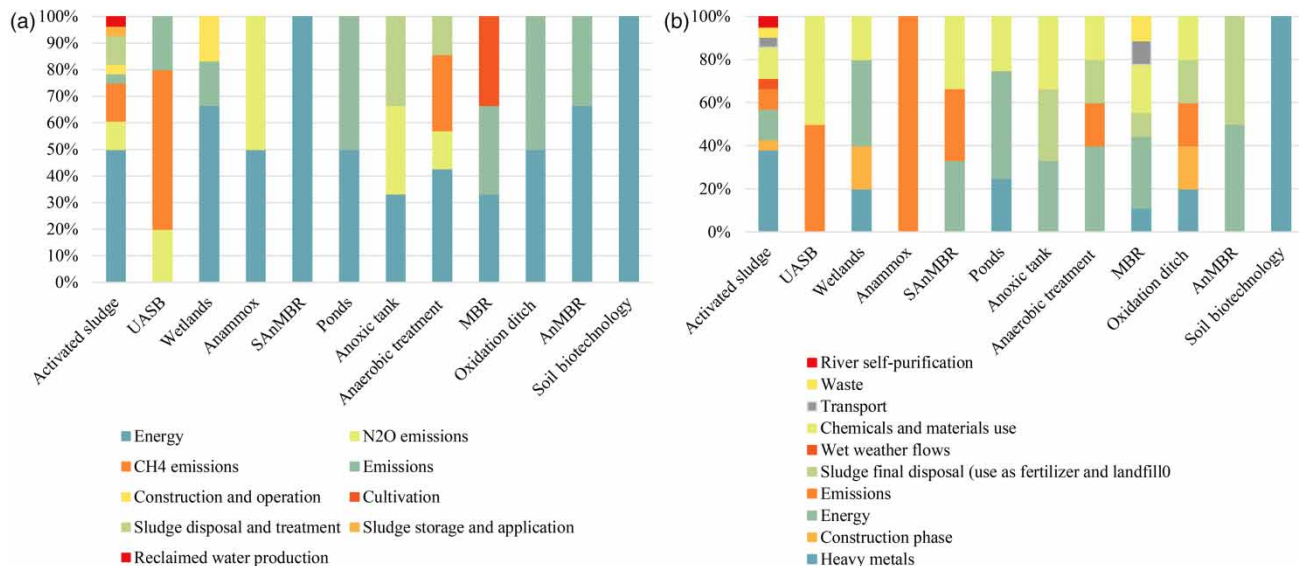


Figure 7 | Most significant processes for environmental impacts, as appointed by authors for (a) global warming and (b) toxicity categories. UASB: upflow anaerobic sludge blanket, Anammox: anaerobic ammonium oxidation, SANMBR: submerged anaerobic membrane bioreactor, MBR: membrane bioreactor, AnMBR: anaerobic membrane bioreactor.

coverage. Since most of the treatments are biological and various parameters are dependent on time, such as population, temperature, and rain regime, studies should acknowledge when and where the data is from and which technology does it rely on. Another important point is to know how long the data collection must take. One year of data is ideal, especially regarding countries with defined seasons and significant weather variations. Since not all information requires the same data quality, studies should model their systems a

couple of times and improve the quality of the main parameters that correlate in the impact categories researched.

This work concludes that a complete LCI, either presented in the paper or the supplementary materials, should include: (1) database with version; (2) modifications made to the database used to fit the goals; (3) data from primary sources or estimated; (4) methodology for data estimations; (5) data quality; and (6) process identification in the database chosen.

Life cycle impact assessment

The LCIA must be correlated with the software used and its version, the midpoint and endpoint categories used, and the LCIA methodology and version. For the midpoint categories, studies should consider (when applied to the study goal) eutrophication, climate change or global warming, acidification, and toxicity, since they present a great relevance for WWTPs. Moreover, authors should strive to include new categories recently created, such as odor (Cadena *et al.* 2018) and bacterial oxygen depletion (Bai *et al.* 2018).

An important point to improve in future studies is the discussion section, mostly due to the lack of other material to compare. LCAs can be as distinguished as a fingerprint and the comparison with other studies, although sometimes possible, may not be very significant. In this context, authors should strive to compare (when they find similar studies), but should also present the main causes of the environmental impacts perceived in their systems. This information can lead to a further understanding of the systems analyzed, the development of new optimized systems, and understanding of other life cycle phases such as transportation and material manufacturing. Another important point is the division of the impact by the life cycle phase (construction, operation, maintenance, and demolition), to improve the comparability of results found, and the understanding of the relevance of each phase for each technology system, which is a shortcoming identified.

Interpretation

Most of the papers selected did not present sensitivity or uncertainty analysis. Although uncertainty analyses may be inaccessible because they require high computational power and software availability, one or two sensitivity analyses are encouraged, especially regarding the main processes in which the environmental impact of the work is derived. Some important sensitivity analyses that can be carried out in a wastewater treatment LCA are (1) energy; (2) transportation; (3) materials use; (4) resource recovery; (5) main emissions; (6) dosages used in the process.

Sensitivity analysis should be carefully chosen and reflect the study goal and scope and the facility studied. For instance, activated sludge systems could apply a sensitivity analysis over the energy input and source, since aeration and sludge treatment line consume a high amount of energy. When testing the recovery of materials such as nitrogen and phosphorus, or the sludge reuse in agriculture,

one should use the sensitivity analysis for transport distances. Other important sensitivity analyses are chemicals used in the process, sludge quantity, wastewater quality, treatment efficiency, transport type, and variation of all parameters that mostly interfere with the environmental impact.

Checklist

A checklist is presented to improve the transparency in future works regarding the LCA of WWTPs (Table 3). Authors could adapt the checklist to fit the scope and goal of the research they are aiming to publish, even for other

Table 3 | LCA of WWTPs – checklist on the basic information needed

Information	Check
Does my study present the goal clearly?	
Does my study state clearly the functional unit used (if using a volume functional unit, authors should specify what type of water they mean and main characteristics)?	
Is the system minimally described so readers will understand which type of system it is, how it works, the efficiency, and main flow characteristics?	
Does my paper specify which stages of the life cycle are evaluated (operational, construction, maintenance, and demolition)?	
Does my article specify if the treatment of sludge is included and which treatment is performed in my framework?	
Does my paper show clearly all software used as the interface for my calculations?	
Does my paper identify the type of LCA conducted (attributorial or consequential)?	
Does my paper describe the type of allocation or the method used to avoid allocation?	
Does my paper indicate the database and version?	
Does my paper indicate the precedence of the data and data quality?	
Does my paper indicate which processes I chose to adapt from the database and how I adapted them to fit my reality?	
Do I state clearly the type of LCA I am conducting and the type of database I used (attributorial or consequential), as well as the reasoning of this choice?	
Does my paper indicate the data used and how calculations were performed to obtain said data?	
Does my paper indicate the LCIA methodology used and any modifications made in the characterization performed? And the version chosen?	

types of systems. The most significant shortcomings observed are covered.

Future research opportunities

One of the future tendencies identified for LCA of WWTPs is the use of data envelopment analysis (DEA) methodology, which can be divided into two groups: (1) energy and (2) environmental. Many selected studies presented the combination of these methodologies (Lorenzo-Toja *et al.* 2015, 2016, 2018).

Another important remark is that authors are now coupling different LCIA methodologies to improve the quality of the results found (De Feo & Ferrara 2017; Longo *et al.* 2017). Although not identified in the selected literature, studies coupling big data and LCA could represent one future front for this type of analysis (Cooper & Kahn 2012).

The authors also identified many opportunities within the LCA of WWTP field, such as studies that focus on the optimization of WWTPs and the application of the methodology in resource recovery systems. The LCA can also be combined with other methodologies such as life cycle cost assessment and social LCA to develop life cycle sustainability assessments. Additionally, the creation of regulations reinforcing the LCA on WWTPs to further develop the environmental analysis throughout the world should be encouraged.

CONCLUSION

In this systematic review of LCA applied to WWTP, most of the shortcomings identified relate to the disclosure of important information, which can increase transparency. A diversity of impact methodologies and categories were identified as well as many different systems and configurations. Some papers presented a very careful and well-thought discussion. However, many methodological aspects are still divergent and there is a lack of comparability on the works.

The most significant challenge identified was data quality and availability, which leads to uncertainties and the use of databases that may not represent well regional data. Furthermore, the quality of the data used in the studies must be related to its timeline and the experiments must be taken according to a detailed methodology. The definition of how to allocate resources and how to account for the avoided impacts in the system is also a common problem. Moreover, the creation and adoption of LCIA

methodologies that can show the environmental impacts locally can benefit future studies.

Filters used to improve the quality of materials selected for review, and the analysis for urban WWTPs are the main limitations of this study. Nevertheless, the authors revealed by such means major drawbacks in the literature that must be addressed.

The results demonstrate the need for the creation of a specific protocol for LCA of urban WWTPs to guarantee comparability between studies and increase transparency. This work is a starting point for scientists in the field and by adopting this, future research could be more concise, transparent, and focused on the most significant gaps found in the literature.

ACKNOWLEDGEMENTS

This study was partly financed by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (College and Graduate Education Improvement Coordination), Brazil (CAPES), Finance Code 001. The authors also acknowledge the financial support given by Fundação de Amparo à Pesquisa e Inovação do Espírito Santo (Espírito Santo Research and Innovation Support Foundation – FAPES) project 107/2019.

DATA AVAILABILITY STATEMENT

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

REFERENCES

- Amores, M. J., Meneses, M., Pasqualino, J., Antón, A. & Castells, F. 2013 *Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach*. *J. Cleaner Prod.* **43**, 84–92. <https://doi.org/10.1016/j.jclepro.2012.12.033>.
- Arashiro, L. T., Montero, N., Ferrer, I., Ación, F. G., Gómez, C. & Garfí, M. 2018 *Life cycle assessment of high rate algal ponds for wastewater treatment and resource recovery*. *Sci. Total Environ.* **622–623**, 1118–1130. <https://doi.org/10.1016/j.scitotenv.2017.12.051>.
- Bai, S., Wang, X., Zhao, X. & Ren, N. 2018 *Characterizing water pollution potential in life cycle impact assessment based on bacterial growth and water quality models*. *Water (Switzerland)* **10**. <https://doi.org/10.3390/w10111621>.
- Bai, S., Zhang, X., Xiang, Y., Wang, X., Zhao, X. & Ren, N. 2019 *HIT.WATER scheme: an integrated LCA-based decision-*

- support platform for evaluation of wastewater discharge limits. *Sci. Total Environ.* **655**, 1427–1438. <https://doi.org/10.1016/j.scitotenv.2018.11.209>.
- Baitz, M., Albrecht, S., Brauner, E., Broadbent, C., Castellan, G., Conrath, P., Fava, J., Finkbeiner, M., Fischer, M., Fullana, I., Palmer, P., Krinke, S., Leroy, C., Loebel, O., McKeown, P., Mersiowsky, I., Möglinger, B., Pfaadt, M., Rebitzer, G., Rother, E., Ruhland, K., Schanssema, A. & Tikana, L. 2013 *LCA's theory and practice: like ebony and ivory living in perfect harmony?* *Int. J. Life Cycle Assess.* **18**, 5–13. <https://doi.org/10.1007/s11367-012-0476-x>.
- Bisinella de Faria, A. B., Spérandio, M., Ahmadi, A. & Tiruta-Barna, L. 2015 *Evaluation of new alternatives in wastewater treatment plants based on dynamic modelling and life cycle assessment (DM-LCA).* *Water Res.* **84**, 99–111. <https://doi.org/10.1016/j.watres.2015.06.048>.
- Brander, M. & Wylie, C. 2011 *The use of substitution in attributional life cycle assessment.* *Greenh. Gas Meas. Manage.* **1**, 161–166. <https://doi.org/10.1080/20430779.2011.637670>.
- Cadena, E., Adani, F., Font, X. & Artola, A. 2018 *Including an odor impact potential in life cycle assessment of waste treatment plants.* *Int. J. Environ. Sci. Technol.* **15**, 2193–2202. <https://doi.org/10.1007/s13762-017-1613-7>.
- Cashman, S., Ma, X., Mosley, J., Garland, J., Crone, B. & Xue, X. 2018 *Energy and greenhouse gas life cycle assessment and cost analysis of aerobic and anaerobic membrane bioreactor systems: influence of scale, population density, climate, and methane recovery.* *Bioresour. Technol.* **254**, 56–66. <https://doi.org/10.1016/j.biortech.2018.01.060>.
- Cooper, J. S. & Kahn, E. 2012 *Commentary on Issues in Data Quality Analysis in Life Cycle Assessment* 499–503. <https://doi.org/10.1007/s11367-011-0371-x>
- Cornejo, P. K., Zhang, Q. & Mihelcic, J. R. 2013 *Quantifying benefits of resource recovery from sanitation provision in a developing world setting.* *J. Environ. Manage.* **131**, 7–15. <https://doi.org/10.1016/j.jenvman.2013.09.043>.
- Corominas, L., Foley, J., Guest, J. S., Hospido, A., Larsen, H. F., Morera, S. & Shaw, A. 2013 *Life cycle assessment applied to wastewater treatment: state of the art.* *Water Res.* **47**, 5480–5492. <https://doi.org/10.1016/j.watres.2013.06.049>.
- De Feo, G. & Ferrara, C. 2017 *Investigation of the environmental impacts of municipal wastewater treatment plants through a life cycle assessment software tool.* *Environ. Technol. (United Kingdom)* **38**, 1943–1948. <https://doi.org/10.1080/09593330.2016.1241306>.
- Diaz-Elsayed, N., Xu, X., Balaguer-Barbosa, M. & Zhang, Q. 2017 *An evaluation of the sustainability of onsite wastewater treatment systems for nutrient management.* *Water Res.* **121**, 186–196. <https://doi.org/10.1016/j.watres.2017.05.005>.
- Earles, J. M. & Halog, A. 2011 *Consequential life cycle assessment: a review.* *Int. J. Life Cycle Assess.* **16**, 445–453. <https://doi.org/10.1007/s11367-011-0275-9>.
- Edelen, A. & Ingwersen, W. W. 2018 *The creation, management, and use of data quality information for life cycle assessment.* *Int. J. Life Cycle Assess.* **23**, 759–772. <https://doi.org/10.1007/s11367-017-1348-1>.
- Ekvall, T. & Finnveden, G. 2001 *Allocation in ISO 14041—a critical review.* *J. Cleaner Prod.* **9** (3), 197–208. [http://dx.doi.org/10.1016/S0959-6526\(00\)00052-4](http://dx.doi.org/10.1016/S0959-6526(00)00052-4).
- Ekvall, T. & Weidema, B. P. 2004 *System boundaries and input data in consequential life cycle inventory analysis.* *Int. J. LCA* **9**, 161–171. <https://doi.org/10.1007/BF02994190>.
- Ensslin, L., Ensslin, S. R., Lacerda, R. T. O. & Tasca, J. E. 2010 *ProKnow-C, Knowledge Development Process – Constructivist. Processo técnico com patente de registro pendente junto ao INPI.* INPI, Rio de Janeiro, Brazil.
- Fang, L. L., Valverde-Pérez, B., Damgaard, A., Plósz, B. G. & Rygaard, M. 2016 *Life cycle assessment as development and decision support tool for wastewater resource recovery technology.* *Water Res.* **88**, 538–549. <https://doi.org/10.1016/j.watres.2015.10.016>.
- Ferenhof, H. A., Vignochi, L., Selig, P. M., Lezana, Á. G. R. & Campos, L. M. S. 2014 *Environmental management systems in small and medium-sized enterprises: an analysis and systematic review.* *J. Cleaner Prod.* **74**, 44–53. <https://doi.org/10.1016/j.jclepro.2014.03.027>.
- Gallego-Schmid, A. & Tarpani, R. R. Z. 2019 *Life cycle assessment of wastewater treatment in developing countries: a review.* *Water Res.* **153**, 63–79. <https://doi.org/10.1016/j.watres.2019.01.010>.
- Garfi, M., Flores, L. & Ferrer, I. 2017 *Life cycle assessment of wastewater treatment systems for small communities: activated sludge, constructed wetlands and high rate algal ponds.* *J. Cleaner Prod.* **161**, 211–219. <https://doi.org/10.1016/j.jclepro.2017.05.116>.
- Hao, X., Wang, X., Liu, R., Li, S., Van, L. M. C. M. & Jiang, H. 2019 *Environmental impacts of resource recovery from wastewater treatment plants.* *Water Res.* **160**, 268–277. <http://dx.doi.org/10.1016/j.watres.2019.05.068>.
- Heimersson, S., Svanström, M., Laera, G. & Peters, G. 2016 *Life cycle inventory practices for major nitrogen, phosphorus and carbon flows in wastewater and sludge management systems.* *Int. J. Life Cycle Assess.* **21**, 1197–1212. <https://doi.org/10.1007/s11367-016-1095-8>.
- Hernández-Padilla, F., Margni, M., Noyola, A., Guereca-Hernandez, L. & Bulle, C. 2017 *Assessing wastewater treatment in Latin America and the Caribbean: enhancing life cycle assessment interpretation by regionalization and impact assessment sensibility.* *J. Cleaner Prod.* **142**, 2140–2153.
- Holloway, R. W., Miller-Robbie, L., Patel, M., Stokes, J. R., Munakata-Marr, J., Dadakis, J. & Cath, T. Y. 2016 *Life-cycle assessment of two potable water reuse technologies: MF/RO/UV-AOP treatment and hybrid osmotic membrane bioreactors.* *J. Membr. Sci.* **507**, 165–178. <https://doi.org/10.1016/j.memsci.2016.01.045>.
- Hwang, J.-H., Church, J., Lee, S.-J., Park, J. & Lee, W. H. 2016 *Use of microalgae for advanced wastewater treatment and sustainable bioenergy generation.* *Environ. Eng. Sci.* **33**, 882–897. <https://doi.org/10.1089/ees.2016.0132>.
- ISO 14040 2006 *Environmental Management – Life Cycle Assessment – Principles and Framework.* ISO, Geneva, p. 28.

- ISO 14044 2006 *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*. ISO, Geneva, p. 46.
- ISO 13315-1 2012 *Environmental Management for Concrete and Concrete Structures – Part 1 : General Principles*. ISO, Geneva, Switzerland, p. 14.
- ISO 13315-2 2014 *Environmental Management for Concrete and Concrete Structures – Part 2*. ISO Geneva, Switzerland, p. 28.
- Kamble, S. J., Chakravarthy, Y., Singh, A., Chubilleau, C., Starkl, M. & Bawa, I. 2017 A soil biotechnology system for wastewater treatment: technical, hygiene, environmental LCA and economic aspects. *Environ. Sci. Pollut. Res.* **24**, 13315–13334. <https://doi.org/10.1007/s11356-017-8819-6>.
- Lam, L., Kurisu, K. & Hanaki, K. 2015 Comparative environmental impacts of source-separation systems for domestic wastewater management in rural China. *J. Cleaner Prod.* **104**, 185–198. <https://doi.org/10.1016/j.jclepro.2015.04.126>.
- Lane, J. L., de Haas, D. W. & Lant, P. A. 2015 The diverse environmental burden of city-scale urban water systems. *Water Res.* **81**, 398–415. <https://doi.org/10.1016/j.watres.2015.03.005>.
- Lee, M., Keller, A. A., Chiang, P.-C., Den, W., Wang, H., Hou, C.-H., Wu, J., Wang, X. & Yan, J. 2017 Water-energy nexus for urban water systems: a comparative review on energy intensity and environmental impacts in relation to global water risks. *Appl. Energy* **205**, 589–601. <https://doi.org/10.1016/j.apenergy.2017.08.002>.
- Lehtoranta, S., Vilpas, R. & Mattila, T. J. 2014 Comparison of carbon footprints and eutrophication impacts of rural on-site wastewater treatment plants in Finland. *J. Cleaner Prod.* **65**, 439–446. <https://doi.org/10.1016/j.jclepro.2013.08.024>.
- Lemos, D., Dias, A. C., Gabarrell, X. & Arroja, L. 2013 Environmental assessment of an urban water system. *J. Cleaner Prod.* **54**, 157–165. <https://doi.org/10.1016/j.jclepro.2013.04.029>.
- Limphitakphong, N., Pharino, C. & Kanchanapiya, P. 2016 Environmental impact assessment of centralized municipal wastewater management in Thailand. *Int. J. Life Cycle Assess.* **21**, 1789–1798. <https://doi.org/10.1007/s11367-016-1130-9>.
- Lin, Y., Guo, M., Shah, N. & Stuckey, D. C. 2016 Economic and environmental evaluation of nitrogen removal and recovery methods from wastewater. *Bioresour. Technol.* **215**, 227–238. <https://doi.org/10.1016/j.biortech.2016.03.064>.
- Longo, S., Frison, N., Renzi, D., Fatone, F. & Hospido, A. 2017 Is SCENA a good approach for side-stream integrated treatment from an environmental and economic point of view? *Water Res.* **125**, 478–489. <https://doi.org/10.1016/j.watres.2017.09.006>.
- Lorenzo-Toja, Y., Vázquez-Rowe, I., Chenel, S., Marín-Navarro, D., Moreira, M. T. & Feijoo, G. 2015 Eco-efficiency analysis of Spanish WWTPs using the LCA + DEA method. *Water Res.* **68**, 651–666. <https://doi.org/10.1016/j.watres.2014.10.040>.
- Lorenzo-Toja, Y., Vázquez-Rowe, I., Amores, M. J., Termes-Rifé, M., Marín-Navarro, D., Moreira, M. T. & Feijoo, G. 2016 Benchmarking wastewater treatment plants under an eco-efficiency perspective. *Sci. Total Environ.* **566–567**, 468–479. <https://doi.org/10.1016/j.scitotenv.2016.05.110>.
- Lorenzo-Toja, Y., Vázquez-Rowe, I., Marín-Navarro, D., Crujeiras, R. M., Moreira, M. T. & Feijoo, G. 2018 Dynamic environmental efficiency assessment for wastewater treatment plants. *Int. J. Life Cycle Assess.* **23**, 357–367. <https://doi.org/10.1007/s11367-017-1316-9>.
- Loubet, P., Roux, P., Guérin-Schneider, L. & Bellon-Maurel, V. 2016 Life cycle assessment of forecasting scenarios for urban water management: a first implementation of the WaLA model on Paris suburban area. *Water Res.* **90**, 128–140. <https://doi.org/10.1016/j.watres.2015.12.008>.
- Lu, B., Du, X. & Huang, S. 2017 The economic and environmental implications of wastewater management policy in China: from the LCA perspective. *J. Cleaner Prod.* **142**, 3544–3557. <https://doi.org/10.1016/j.jclepro.2016.10.113>.
- Lutterbeck, C. A., Kist, L. T., Lopez, D. R., Zerwes, F. V. & Machado, E. L. 2017 Life cycle assessment of integrated wastewater treatment systems with constructed wetlands in rural areas. *J. Cleaner Prod.* **148**, 527–536. <https://doi.org/10.1016/j.jclepro.2017.02.024>.
- Malila, R., Lehtoranta, S. & Viskari, E.-L. 2019 The role of source separation in nutrient recovery – comparison of alternative wastewater treatment systems. *J. Cleaner Prod.* **219**, 350–358. <https://doi.org/10.1016/j.jclepro.2019.02.024>.
- Miller-Robbie, L., Ramaswami, A. & Amerasinghe, P. 2017 Wastewater treatment and reuse in urban agriculture: exploring the food, energy, water, and health nexus in Hyderabad, India. *Environ. Res. Lett.* **12**. <https://doi.org/10.1088/1748-9326/aa6bfe>.
- Mo, W. & Zhang, Q. 2013 Energy-nutrients-water nexus: integrated resource recovery in municipal wastewater treatment plants. *J. Environ. Manage.* **127**, 255–267. <https://doi.org/10.1016/j.jenvman.2013.05.007>.
- Morera, S., Comas, J., Poch, M. & Corominas, L. 2015 Connection of neighboring wastewater treatment plants: economic and environmental assessment. *J. Cleaner Prod.* **90**, 34–42. <https://doi.org/10.1016/j.jclepro.2014.11.047>.
- Morera, S., Corominas, L., Rigola, M., Poch, M. & Comas, J. 2017 Using a detailed inventory of a large wastewater treatment plant to estimate the relative importance of construction to the overall environmental impacts. *Water Res.* **122**, 614–623.
- Moretti, M., Van Passel, S., Camposeo, S., Pedrero, F., Dogot, T., Lebailly, P. & Vivaldi, G. A. 2019 Modelling environmental impacts of treated municipal wastewater reuse for tree crops irrigation in the Mediterranean coastal region. *Sci. Total Environ.* **660**, 1513–1521. <https://doi.org/10.1016/j.scitotenv.2019.01.043>.
- Muñoz, I., Portillo, F., Rosiek, S., Batlles, F. J., Martínez-Del-Río, J., Acasuso, I., Piergrossi, V., De Sanctis, M., Chimienti, S. & Di Iaconi, C. 2019 Prospective environmental and economic assessment of solar-assisted thermal energy recovery from wastewater through a sequencing batch biofilter granular reactor. *J. Cleaner Prod.* **212**, 1300–1309. <https://doi.org/10.1016/j.jclepro.2018.12.074>.
- Niero, M., Pizzol, M., Bruun, H. G. & Thomsen, M. 2014 Comparative life cycle assessment of wastewater treatment in Denmark

- including sensitivity and uncertainty analysis. *J. Cleaner Prod.* **68**, 25–35. <https://doi.org/10.1016/j.jclepro.2013.12.051>.
- Papa, M., Alfonsín, C., Moreira, M. T. & Bertanza, G. 2016 Ranking wastewater treatment trains based on their impacts and benefits on human health: a ‘biological assay and disease’ approach. *J. Cleaner Prod.* **113**, 311–317. <https://doi.org/10.1016/j.jclepro.2015.11.021>.
- Piao, W., Kim, Y., Kim, H., Kim, M. & Kim, C. 2016 Life cycle assessment and economic efficiency analysis of integrated management of wastewater treatment plants. *J. Cleaner Prod.* **113**, 325–337. <https://doi.org/10.1016/j.jclepro.2015.11.012>.
- Pintilie, L., Torres, C. M., Teodosiu, C. & Castells, F. 2016 Urban wastewater reclamation for industrial reuse: an LCA case study. *J. Cleaner Prod.* **139**, 1–14. <https://doi.org/10.1016/j.jclepro.2016.07.209>.
- Pretel, R., Robles, A., Ruano, M. V., Seco, A. & Ferrer, J. 2016 Economic and environmental sustainability of submerged anaerobic MBR-based (AnMBR-based) technology as compared to aerobic-based technologies for moderate-/high-loaded urban wastewater treatment. *J. Environ. Manage.* **166**, 45–54. <https://doi.org/10.1016/j.jenvman.2015.10.004>.
- Risch, E., Loubet, P., Núñez, M. & Roux, P. 2014 How environmentally significant is water consumption during wastewater treatment?: application of recent developments in LCA to WWT technologies used at 3 contrasted geographical locations. *Water Res.* **57**, 20–30. <https://doi.org/10.1016/j.watres.2014.03.023>.
- Risch, E., Gutierrez, O., Roux, P., Boutin, C. & Corominas, L. 2015 Life cycle assessment of urban wastewater systems: quantifying the relative contribution of sewer systems. *Water Res.* **77**, 35–48. <https://doi.org/10.1016/j.watres.2015.03.006>.
- Sabeen, A. H., Noor, Z. Z., Ngadi, N., Almuraisy, S. & Raheem, A. B. 2018 Quantification of environmental impacts of domestic wastewater treatment using life cycle assessment: a review. *J. Cleaner. Prod.* **190**, 221–233. <https://doi.org/10.1016/j.jclepro.2018.04.053>.
- Sena, M. & Hicks, A. 2018 Life cycle assessment review of struvite precipitation in wastewater treatment. *Resour. Conserv. Recycl.* **139**, 194–204. <https://doi.org/10.1016/j.resconrec.2018.08.009>.
- Shuai, W., Chen, N., Li, B., Zhou, D. & Gao, J. 2016 Life cycle assessment of common reed (*Phragmites australis* (Cav) Trin. ex Steud) cellulosic bioethanol in Jiangsu Province, China. *Biomass Bioenergy* **92**, 40–47. <https://doi.org/10.1016/j.biombioe.2016.06.002>.
- Vieira, D. R., Calmon, J. L. & Coelho, F. Z. 2016 Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: a review. *Constr. Build. Mater.* **124**, 656–666. <https://doi.org/10.1016/j.conbuildmat.2016.07.125>.
- Weidema, B. P., Pizzol, M., Schmidt, J. & Thoma, G. 2018 Attributional or consequential life cycle assessment: a matter of social responsibility. *J. Cleaner Prod.* **174**, 305–314. <https://doi.org/10.1016/j.jclepro.2017.10.340>.
- Xiong, W., Li, Y., Zhang, W., Ye, Q., Zhang, S. & Hou, X. 2018 Integrated multi-objective optimization framework for urban water supply systems under alternative climates and future policy. *J. Cleaner Prod.* **195**, 640–650. <https://doi.org/10.1016/j.jclepro.2018.05.161>.
- Zang, Y., Li, Y., Wang, C., Zhang, W. & Xiong, W. 2015 Towards more accurate life cycle assessment of biological wastewater treatment plants: a review. *J. Cleaner. Prod.* **107**, 676–692. <https://doi.org/10.1016/j.jclepro.2015.05.060>.

First received 12 August 2020; accepted in revised form 16 December 2020. Available online 30 December 2020