A critical review on Life Cycle Assessment and plant-wide models towards emission control strategies for greenhouse gas from wastewater treatment plants

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Abstract

For decades, there has been a strong interest in mitigating greenhouse gas (GHG) emissions from wastewater treatment plants (WWTPs). Numerous models were developed to measure the emissions and propose the quantification. Existing studies looked at the relationship between GHG emissions and operational cost (OCI), which is one of the most important indicators for decision-makers. Other parameters that can influence the control strategies include the effluent quality (EQI) and total environmental impacts. Plant-wide models are reliable methods to examine the OCI, EQI and GHG emissions while Life cycle assessment (LCA) works to assess the potential environmental impacts. A combined LCA and plant-wide model proved to be a valuable tool evaluating and comparing strategies for the best performance of WWTPs. For this study involving a WWTP, the benchmark model is used while LCA is the decision tool to find the most suitable treatment strategy. LCA adds extra criteria that complement the existing criteria provided by such models. Complementing the cost/performance criteria is proposed for plant-wide models, including environmental evaluation, based on LCA, which provides an overall better assessment of WWTPs. It can capture both the dynamic effects and potential environmental impacts. This study provides an overview of the integration between plant-wide models and LCA.

Keywords: Life cycle assessment, greenhouse gas, emission control, wastewater treatment plant, plant-wide model

1. Introduction

Wastewater treatment plants are important systems in the water treatment sector because they ensure the quality of the aquatic environment. However, under various treatment processes, given their usage of chemicals and energy, greenhouse gas are produced and emitted from wastewater treatment plants. The quantity of these emissions is increasing and been reported in the Global Atlas of the three major types of greenhouse gas emissions for the period 1970-2012 (Janssens-Maenhout et al., 2017). Therefore, wastewater treatment plants do contribute to global warming. GHG emissions become the key factor when evaluating the overall performance of a WWTP. The inclusion of GHG emissions is an additional criterion when evaluating control strategies in a WWTP, offering a better idea about their overall sustainability (Flores-Alsina et al., 2014). In recent years, various methods of quantification and measurement have been proposed in order to increase the available data and literature on GHG emissions. It is also pointed out that our incomplete knowledge of GHG production influences the output results. The direct measuring methods have certain uncertainties and limitations due to the variability of the influent, complexity of treatment process, operational time and different standard evaluation criteria.

There is a need for developing new tools to estimate and evaluate GHG emissions from different processes that prevent or mitigate their generation in WWTPs (Flores-Alsina et al., 2011). Mathematical models of GHGs are useful tools to assess the quantity of emissions and examine different mitigation approaches. Emissions under various operating conditions and from different units could be estimated with great accuracy by using these models. Control strategies could be developed for these models to include GHG emissions during design, operation and optimisation of WWTPs (Mannina et al., 2016). As the results of using different models in different plant configurations and a variety of influent wastewater characteristics, all treatment systems and other related activities should be evaluated. Flores- Alsina et al. (2011)

found influent, effluent and operational variables at each simulation step; hence, the control strategies might influence the conditions of GHG generation and emissions. Therefore, multiple evaluation criteria, which include effluent quality, economic cost and GHG emissions, should be involved in the operational strategy. Plant-wide models were built for the design and testing of control strategies in WWTPs. Existing studies focus on either implementation of the control on these models or adapt the benchmark framework for real-life plants (Barbu et al., 2017).

Evaluating the control strategies for WWTP via models has several uncertainties regarding using different mathematical models, different plant configuration, a variety of influent characteristic, and numerous environmental indicators. Life Cycle Assessment (LCA) was suggested as something that can complete the performance assessment. Of the different methodologies available in estimating the environmental impacts of WWTPs, LCA as an environmental management tool can investigate a product or a service throughout its whole life cycle, from raw material to production, use and disposal (Nausad, 2018).

Use of LCA ensures that all environmental impacts are analysed within the LCA framework and this helps to avoid shifting problems from one place to another. In the wastewater treatment field, LCA was applied in the 1990s and is considered an effective tool to evaluate the environmental effects of WWTPs in both design and operation (Corominas et al., 2013). During the last two decades, LCA has answered several concerns within the wastewater treatment industry. Numerous research has been conducted and reviewed in recent years demonstrating different LCA application methods (Sabeen et al., 2018).

Several reviews on LCA studies dealing with WWTPs have been published. Corominas et al. (2013a) conducted a review of 45 articles. According to their paper, previous studies focused on identifying methods and how they communicated the results. All of the reviewed studies defined their respective goals and scopes. One-third of them provided inventory data. Eighty-two per cent addressed the impact assessment, while thirty-eight per cent did not indicate the methodology. Only thirty-three per cent provided the assessment procedure and limitations of the approach and/or determining the parameters that influence the LCA outcome (Corominas, Foley et al., 2013). The purpose of this paper is to determine the need for guidelines for LCA studies when applied to WWTPs and the upcoming challenges in the water treatment field.

Friedrich et al. (2007) reviewed the use of LCA in the water treatment sector and its local applications. Their paper reflected the limitations of the LCA tool. Aspects of these limitations related to the tool and framework in general while the other problems emerged from the specific locations. The general shortcomings of LCA are listed as follows: the energy required, raw materials, toxicological impacts which are included without an analysis of the gap. The consumption of water and land, and habitat alterations are mostly not considered. Finally, the environmental impacts are underestimated due to insufficient data (Friedrich et al., 2007).

A review of 22 studies using LCA in wastewater treatment focused on the impact of toxicity, was carried out by Larsen et al. (2007). Their findings hightlighted the importance of different stages in LCA. The "use stage" is the most important process due to energy consumption, the level of GHG emissions, effluent, and sludge production (Larsen et al., 2007). The environmental impacts, which include an energy-related category and chemical-related component, play an important role in an LCA study of wastewater treatment technology. The objective of this research was developing a methodology that could analyse impacts of micro-pollutants and pathogens in the life cycle impact assessment.

Zang et al. (2015) reviewed 53 LCA studies on biological WWTPs and indicated the source of each impact category that may influence the results. In their analysis, the development and application of the model are reviewed to improve accuracy. The authors showed the current use of LCA in WWTPs. According to their study, LCA is normally employed to compare between wastewater treatment systems based on their environmental impacts. Another benefit of LCA is to evaluate the influence of one or more WWTPs to identify the limitations of the process. The third purpose for using LCA is to integrate WWTPs with the whole water use and treatment cycle, which consists of all processes from water supply to wastewater treatment. Finally, LCA can be applied when some impact categories need more focus or further development (Zang et al., 2015). This paper also indicated the influence of GHG on global warming and the surrounding technological systems of the WWTPs affecting the LCA results. For example, in the methane recovery process, when converting biogas into energy, the material for energy conversion would contribute a significant amount of GHG emissions.

Sabeen et al. (2018) reviewed numerous papers published from 1990 to 2016 that have used LCA to evaluate the domestic wastewater treatment processes. This article reviewed how LCA was applied to cover the objectives, boundaries, functional units (FUs) and life cycle impact assessment (LCIA). According to Sabeen et al., using LCA helps to improve some aspects of municipal wastewater treatment. However, choosing different FUs, system boundaries or LCIA methods affect the total results. Therefore, in future studies more attention should be paid when selecting FU.

The most recent review on the application of LCA to wastewater treatment in developing countries was conducted by Gallego-Schmid et al. (2019). This paper assessed 43 articles and indicated that the sources and technical parameters could influence the quality of LCA when considering GHG emissions. Technical parameters include influent wastewater quality, efficiency in removing pollutants, treatment size, and treatment technologies (Gallego-Schmid et al., 2019).

To the best of the our knowledge, no review has yet investigated the GHG emissions estimation methods when using LCA to evaluate the total environmental impacts. There are numerous strategies applied to quantify GHG emissions. However, the assessment of different control strategies is qualitative, not quantitative (Barbu et al., 2017). To capture both the plant's performance and environmental impact evaluation, including GHG emissions, LCA and plant-wide models were combined in some prior studies (Meneses et al., 2015, Arnell et al., 2017). The integration of LCA and other benchmarking tools to develop successful mitigation strategies for GHG emissions from WWTPs has never been reviewed previously. This study aims to provide an overview of the LCA application in evaluating the total environmental impact, including plant-wide models to quantify GHG emissions from WWTPs. The scope of the review includes available journals articles, which consider and provide results for GHG emissions. This paper also proposes an advanced integration of plant-wide models within the LCA procedural context.

2. Method and materials

2.1.Method

This paper is structured as can be seen in Figure 1: first, the application of LCA and plant-wide models are presented to describe the gap of the existing methods; then the reviewed studies are analysed in detail. The LCA reviewed papers are examined follow four phases: goal and scope, inventory, impact assessment, and interpretation in order to investigate the common elements, the distinguishing conditions and the shortage performance. Numbers of articles that conduct plant-wide models to measure GHG emissions were inspected to explore the pros and cons. The opportunities for future reseach are based on limitations of different applied methods.

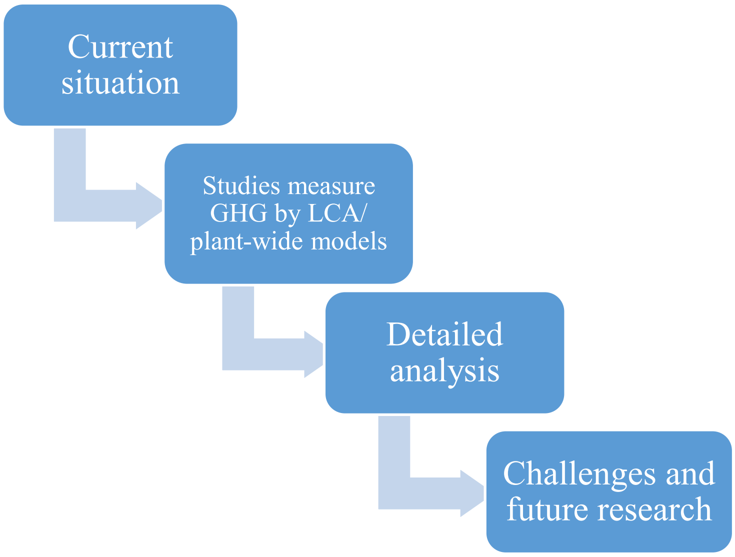

Figure 1. Framework for the evaluation process proposed in this study

2.2. Materials

2.2.1. LCA

LCA completes the whole picture as much as is possible, and all the environmental impacts are taken into account (Guinée, 2002). Use of LCA ensures that all environmental impacts are analysed within the LCA framework. There are three types of LCA models, namely the process-based LCA, input-output LCA, and hybrid LCA (Chen et al., 2012). The first type focuses on energy and materials flow in a manufacturing process, while input-output LCA emphasises the environmental data (Awad et al., 2019). The application of LCA to WWTP is illustrated in Figure 2.

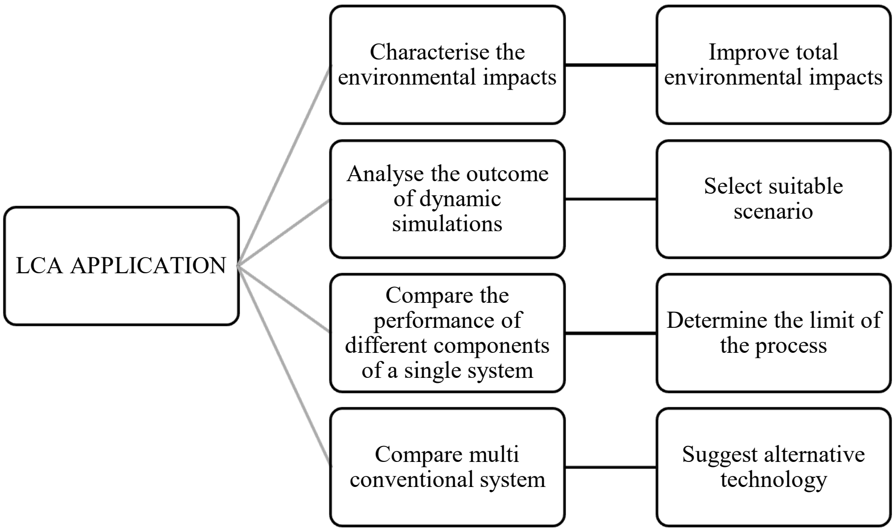

Figure 2. The advantages of using LCA in WWTPs

Using LCA has several benefits as listed below. LCA can determine what technique and management tools provide the best environmental performance (Niero et al., 2014). LCA aims to determine the environmental impact indicators by analysing the emissions from all relevant processes (Yoshida et al., 2014). LCA can identify improvement alternatives for a single plant and to compare different technologies. LCA could be applied to evaluate different types of WWTPs, to compare the environmental impacts (Delre et al., 2019), and to select the best treatment unit process operating scenario (Tangsubkul et al., 2006).

Despite the advantages, LCA has some limitations as follow. Firstly, the results and influence indicators do vary among papers. The reason for this may due to different assessment methods, simulated inventory data, and integration of different models to quantify the environmental impacts (Zang, Li et al., 2015). Secondly, although the environmental impacts of WWTPs are assessed in detail by using LCA, the economic variables are excluded from LCA because they might affect the control strategies. Thirdly and finally, the data availability and data quantity are limited in the life cycle inventory. In some cases, the researcher used secondary data to model effluent emissions (Niero, Pizzol et al., 2014). In other cases, the impact categories were site-dependent (Corominas et al., 2013).

Existing studies have limited scope, either in terms of alternative processes, size of facility or exclusion of significant aspects of the WWTP system (Foley et al., 2010). A limited number of studies have examined the relative environmental impacts of different treatment standards. As research has developed over the years, the objective of LCA research has changed from protecting human health, minimising the consumption of finite resources, reducing the amount of energy required, and reusing pollutants so that they can help in the nutrients recycling process.

2.2.2. Plant-wide models for GHG emissions calculation

WWTPs include many different processes and these comprise biological, transports and hydraulic phenomena. These factors make it difficult to propose control and operation alternatives. For a better understanding of GHG emissions that originate from wastewater treatment plants, models are used as effective and low-cost tools to examine the new technologies and control strategies in GHG management. The application of models to estimate and mitigate GHG estimation has been demonstrated for many years (Bani Shahabadi et al., 2009). Furthermore, improving measurement techniques to reduce uncertainty related to GHG emissions, means that models can describe the GHG production from each process in the WWTPs (Corominas et al., 2012). Therefore, the modelling of GHG emissions from WWTPs was proposed in many publications to provide an accurate estimate of how much GHG was being emitted from wastewater treatment plants (Barbu, Vilanova et al., 2017).

According to previous research, these models can be divided into three main types. The first group, which has a high level of uncertainty and variability, consists of the empirical models based on data for emission factors at treatment units (Pagilla et al., 2009). The second group includes simple comprehensive process-based models at treatment units (Corominas, Flores-Alsina et al., 2012). The third group consists of dynamic mechanistic models at treatment units or plant scale (Mannina, Ekama et al., 2016). For a quick evaluation of GHG emissions, the second group is more popular than the third one (Mannina et al., 2019). The process models combine with instrumentation, control and automation (ICA) to create the benchmarking tool for assessment.

The benchmark is a simulation environment consisting of a plant layout, a simulation model, influent loads, treatment procedure and a set of evaluation criteria. Benchmark models are effective tools for the design and testing of the control strategies of WWTPs, and their function is to overcome the difficulties in engineering techniques (Barbu, Vilanova et al., 2017). The first version, named Benchmark Simulation Model no. 1 (BSM1), was proposed in 2002 to develop efficient control strategies for WWTPs (Copp, 2001) and then followed by the BSM2 in 2007. Both the BSM1 and BSM2 include simulation for all treatment units, influent loads, test procedures and evaluation criteria. However, the BSM1 does not allow for evaluation of the interaction between processes, only local strategies can be evaluated. The BSM2 is available for different simulation platforms so it can easily to compare the results of different control strategies of different platforms (Henze et al., 2000). The BSM2 consists of existing models that can describe processes in the WWTP. It includes all the units within the WWTP, and makes it possible to fully evaluate the plant's performance. This model consists of the biological reactions, liquid-gas interactions and GHG production as well. BSM2 calculates the GHG through the following stages: biotreatment, sludge treatment, sludge reuse, chemical usage, power consumption and biogas usage. Many studies use benchmarks on applying control strategies by simulation or on building control frameworks in real plants (Zhou et al., 2011, Santín et al., 2015, Santín et al., 2017). The limitation of BSM2 is that the reduction of nitrate to nitrogen is considered as a one-step process that leads to N_2O production, which cannot be accurately determined (Sweetapple et al., 2013).

An extended version of the BSM2, BSM2G, was proposed later on. BMS2G includes GHG emissions within the model and considers all the units in which the emissions may occur (Flores-Alsina, Corominas et al., 2011, Corominas, Flores-Alsina et al., 2012). This model allows the dynamic evaluation of the GHG emissions in the biological treatment units. BSM2G was employed in some case studies to investigate the influence of some control actions and operational strategies on GHG emissions (Flores-Alsina, Corominas et al., 2011, Sweetapple et al., 2015).

The diffusive emissions estimation model (DEEM) was developed to focus on CO_2 and N_2O emissions originating from biological processes (Rodriguez-Garcia et al., 2012). The biological model was divided into four main categories: oxidation of organic matter, nitrification, denitrification and hydrolysis. DEEM takes into account the CO_2 emissions associated with endogenous decay and microbial growth of autotrophs. N_2O can be captured in the nitrification and denitrification processes where the possibility of AOB reducing nitrite and the possibility of N_2O increasing due to NO inhibition are considered. DEEM can be applied only to the water line, but nonetheless it presents the benefit of simplicity and is suitable for LCA.

A new plant-wide model was developed by Mannina et al. (2019), which can quantify both direct and indirect GHG emissions from the biological and physical processes of a WWTP. This model considers both the contribution of the water line and the sludge line. The model is based on COD, TSS mass balance. The novel features of the model include the following mass-balance-based model regarding nitrogen; a two-step nitrification process; and the ability to quantify N_2O generation both in dissolved and gas forms (Mannina, Rebouças et al., 2019).

Numerous of existing models were developed but none of them consists of multi-criteria evaluation combining GHG with effluent quality and operational cost. Moreover, each models has limitations in measuring GHG emissions due to complex condition. Therefore, more effort should be paid on improving the accuracy of quantifying GHG emissions.

3. The current use of LCA applications to WWTP

While numerous LCA studies investigate the total environmental impacts and potential outcomes from a whole wastewater treatment system cycle, few examined the relevant environmental influences, especially with reference to GHG emissions from wastewater treatment plants. When considering GHG emissions from WWTPs, the majority of LCA studies concentrate on: firstly, carbon dioxide emissions originating from energy consumption; and secondly, methane emissions from sludge treatment. To the best of our knowledge, only 24 studies quantify GHG emissions when using LCA to evaluate the WWTPs performance as can be seen in Table 1. The papers which quantified the volume of GHG emissions from WWTPs while doing life cycle assessment were selected for review in this study.

Table 1. Articles included in the review and main characteristics

Reference	GHG	Method	Goal	Process
(Emmerson et al., 1995)	CO_2	Estimation	Evaluate LCA framework and alternative process options	All treatment processes, energy consumption
(Vidal et al., 2002)	CO_2, CH_4, N_2O	ASM1	Assess the environmental outcomes in a WWTP under three scenarios	Energy consumption and sludge treatment

(Houillon et al., 2005)	CO_2, CH_4, N_2O	Literature review	The contribution of energy and emissions to global warming	Sludge treatment process
(Hospido et al., 2007)	CH_4, N_2O	Literature review	Evaluate the most common technical options to remove organic matter	Sludge treatment
(Foley, de Haas et al., 2010)	CO_2, CH_4, N_2O	BioWin simulator	Using LCA framework to analyse alternative process options	All treatment processes
(Wu et al., 2010)	CO_2, CH_4	Not specificed	Assess a WWTP based on energy and material flows	All treatment processes
(Pan et al., 2011)	CO_2, CH_4, N_2O	IPCC	Estimate GHG from a vertical subsurface flow constructed wetland; and	All treatment processes, energy consumption

			compare with a group of five WWTPs by using LCA	
(Rodriguez-Garcia et al., 2011)	N_2O	IPCC	Assess the environmental performance of 24 WWTPs using LCA with Eutrophication Potential, GWP and operation costs	Sludge treatment
(Godin et al., 2012)	CH_4, N_2O	IPCC	Propose a new methodology to perform LCA on WWTPs	All treatment processes
(Wang et al., 2012)	CO_2, CH_4, N_2O	Literature review	Employ LCA to construct and evaluate 6 AAO wastewater treatment systems to meet standards	Biological treatment process and energy consumption

(Wang et al., 2012)	CO_2 CH_4 N_2O	BioWin simulator	To choose the wastewater treatment processes that mitigate the environmental impacts and promote bioenergy and nutrient recovery	Biological treatment process and energy consumption
(Corominas, Larsen et al., 2013)	CO_2, CH_4, N_2O	Neptune Simulation Benchmark (NSB)	Using LCA to evaluate the environmental impacts of enhancing strategies applied to wastewater nutrient removal	Biological treatment process and energy consumption
(Zhu et al., 2013)	CO_2, CH_4, N_2O	Literature review	Present a methodology to evaluate the environmental impacts of	Biological treatment process and energy consumption

			process performance	
(Cao et al., 2013)	CO_2 equivalent	Literature review	LCA was used to evaluate and compare the energy and GHG emissions implications of two sewage sludge-to-energy systems	Energy consumption and sludge treatment
(Rodriguez-Garcia et al., 2014)	CO_2, CH_4, N_2O	Literature review	The potential environmental impacts of 3 different side-stream treatment technologies were assessed by LCA	All treatment processes
(Yoshida, Clavreul et al., 2014)	CO_2, CH_4, N_2O	IPCC, direct measurement and literature	The influence of data inventory to LCA outcomes	All treatment processes

(Lorenzo-Toja et al., 2016)	CH_4, N_2O	Direct measurement	The role of direct GHG emissions in the GWP of two WWTPs	All treatment processes
(Piao et al., 2016)	CH_4, N_2O	Assumed to be based on literature and IPCC	Evaluate several WWTP based on LCA and economic efficiency analysis	All treatment processes, energy consumption
(Lu et al., 2017)	CO_2, CH_4, N_2O	Not specified	Complement the economic criteria and environmental implications with suggested management policies	Biological treatment process
(Casas Ledón et al., 2017)	CO_2, CH_4, N_2O	Not specified	LCA was used to assess GHG emissions, environmental remediation costs and the	All treatment processes, energy consumption

			specific environmental remediation costs	
(Garfí et al., 2017)	CO_2, CH_4, N_2O	Literature review	Three wastewater treatment systems were assessed to compare the total environmental impacts	All treatment processes
(Polruang et al., 2018)	CO_2, CH_4, N_2O	IPCC	The environmental impacts of seven WWTPs were investigated	All treatment processes, energy consumption
(Awad, Gar Alalm et al., 2019)	N_2O, CH_4, CO_2	Literature review	LCA was applied to four scenarios to study the environmental impacts of a WWTP	Biological treatment Sludge treatment

(Delre, Hoeve et al., 2019)	ten	CO_2, CH_4, N_2O	IPCC		LCA was used to calculate the site-specific carbon footprints for WWTPs	The whole plants

The level of coverage is illustrated in four main steps for the LCA in Figure 3 and then discussed in the following sections.

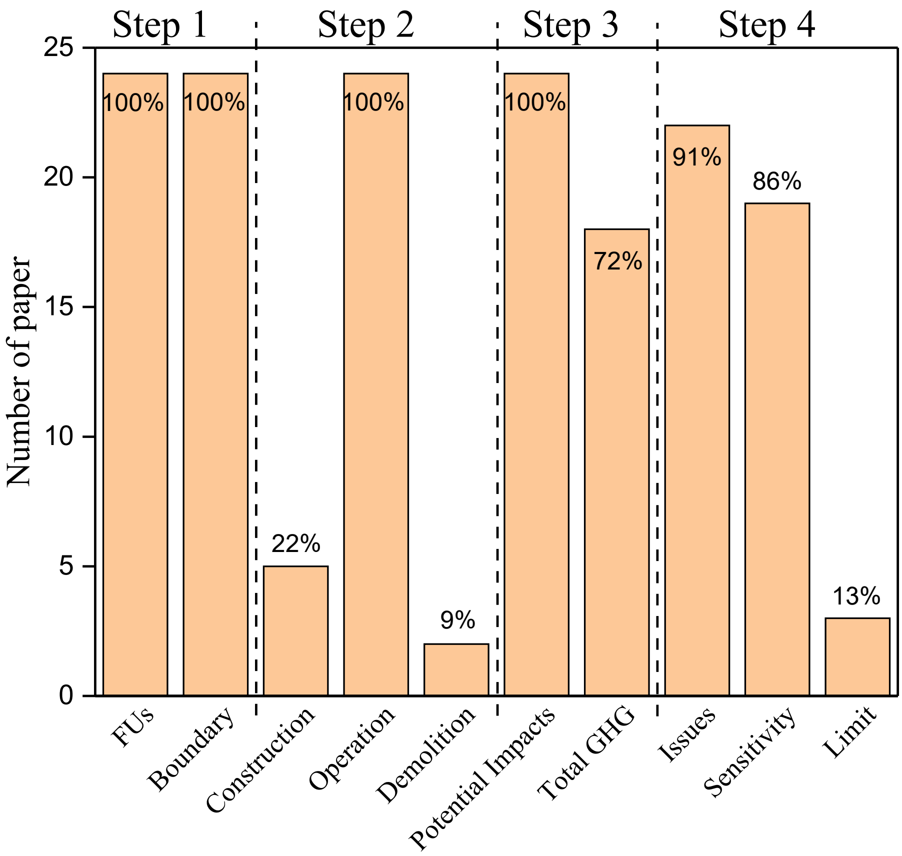

Figure 3. Level of LCA coverage in 25 reviewed papers

3.1. Goal and scope definition

Goal and scope definition is the first step to understand the main purpose of the assessment. It is necessary to describe in detail the function of the systems and to ensure they operate exactly as determined in the event where different WWTPs are being compared. The functional unit (FU) should be clarified. During this step, reference flow is verified to measure product components and materials. All data used in the LCA must be calculated or scaled by the reference flow. Futhermore, all the reviewed papers have identified the FU and described the system boundary.

The FU provides a reference from which inputs and outputs of the process can be standardised. The potential impacts of a WWTP can be calculated and referred to the FU. When defining the FU of a WWTP, different choices were selected. The most common FU is the quantity of treated water at a certain time (m^3d^{-1}), named FU1; it is based on the realistic data as used in 86% of reviewed articles. Some studies chose FU based on treated wastewater associated with a population equivalent (PE) to minimise the difference between the influent composition and flow. In addition to this, FU considers the removal of nutrients and organic matter and this is known as FU2 (kg PO_4^{3-} eq) (Zhu, Liu et al., 2013). FU1 has the ability to indicate the differences between facilities with reference to influent characteristics, while FU2 focuses on the differences between environmental and economic costs of mitigating the potential eutrophication of the effluent (Rodriguez-Garcia, Molinos-Senante et al., 2011). When investigating the pollution removal capacities of the WWTPs, Delre et al. (2019) used the FUs in term of 1 kg of carbon removed, 1 kg of total nitrogen removed, and 1 kg of phosphorus removed. The reason for choosing these FUs was to separate the pollution removal abilities according to the relevant pollutant. The life-span of the plants has improved from fifteen years (Emmerson, Morse et al., 1995) to twenty years (Foley, de Haas et al., 2010) and now their maximum life-span is fifty years (Piao, Kim et al., 2016).

System boundary definition plays an important role in describing which processes will be included or excluded from the system, so the system boundary should be consistent with the objectives of the study. Choosing the system boundary is one of the challenges when implementing LCA. Various system boundaries lead to different results because choosing the system boundary defines which flows of information, energy or material transfer from one system to another (Pan et al., 2018). With reference to GHG emissions, only 9% of the papers could be defined as the "Cradle to Grave" approach, and 22% represented the "Cradle to Gate" research. Most papers focus on the "Gate to Gate" analysis when only the operational phases are being considered. Among the reviewed articles, half of these considered all treatment processes in the water line and sludge line contexts. Three of these focused on sludge treatment only. It was concluded that the construction phase contributed to a negligible impact compared with the operational phase. The effectiveness of these boundary influences on the LCI is discussed in the following section.

3.2. LCI – inventory analysis

LCI is a list of all the material and energy inputs and outputs. This step includes the collection and definition of inputs and outputs of a system throughout its life cycle. LCI is defined as the procedure of data collection and data calculation. For example, inputs comprise raw materials, energy, products or semi-finished products, which are outputs from other processes. Conversely, outputs are emissions, products, and semi-finished products, energy, which are emitted to the environment or used in another process. The input and output data are based on the boundary selection in step 1. The construction and demolition processes are normally excluded from WWTP studies because the operation stage contributes approximately 80% of environmental impacts (Polruang, Sirivithayapakorn et al., 2018). Yoshida et al. (2014) conducted a research study to determine the influence of the inventory data on the outcomes of an LCA study.

- Data availability

One of the most critical issues is establishing reliable inventory data (Yoshida, Clavreul et al., 2014). Data collection is time- and labor-consuming because establishing the on-site data monitoring process is expensive or even impossible in some cases. Due to the lack of data, some processes were excluded from the studies and this meant that the output from the whole cycle and its impact on the environment was underestimated. The input data was based on the WWTP design standards, environmental reports, plant operator communications or on-site measurements. The output data was obtained from on-site measurements, modelling or simulations. Of the 20 papers that investigated on the treatment processes only, 9 of them covered all the treatment stages whilst the number of papers reviewed biological and sludge treatment were 6 and 5, respectively. Regarding GHG emissions, 68% of the articles quantified total GHG emissions in terms of carbon dioxide, methane and nitrous oxide. The remaining papers covered only one or two gases in their research.

- Data quality

The number of reviewed papers indicating the method to quantify GHG emissions based on the literature review and IPCC guidelines, accounted for 63.6%. Using IPCC has some limitations, such as the exclusion of direct carbon dioxide emissions, uncertainties with default emissions factors, and the accuracy of default data. There are two types of emission factors used to report the quality and quantity of the data. Most of the emission factors are based on the IPCC guidelines or have been calculated on-site. To ensure the quality and reduce the uncertainties, the data need to be updated and less than three years old. Approximately 20% of the studies excluded the evaluation method, which was similar to the proportion of articles assessing GHG emissions through the use of models. Only one study was conducted with an on-site measurement technique (Lorenzo-Toja, Alfonsín et al., 2016). The uncertainties of this method might relate to technical problems, the number of sampling points, the position of sampling points, and the operator’s experience.

3.3. LCIA

The impact assessment step aims to study the potential effects on human health, the availability of resources, and the natural environment. This step makes the results of an LCA easier to interpret. The energy use and emissions generated are classified and characterised into impact categories and impact potentials, including global warming, acidification and eutrophication (UNEP, 2003, ISO, 2006). Because of the limitation of the boundaries, the reviewed papers mostly considered the environmental impacts associated with the operation phase, which included primary, secondary, tertiary treatments, and effluent discharge.

Total GHG emissions from WWTP, including methane, carbon dioxide and nitrous oxide, are the sum of direct and indirect emissions. The direct emissions are GHG emitted from each treatment processes within the system boundary while the indirect emissions are related to energy consumption. For the treatment processes, the energy inputs are strongly correlated to the potential outcomes such as global warming, and contributing up to 70% of several impact categories (Sabeen, Noor et al., 2018). However, half of the reviewed papers excluded energy utilisation.

3.4. Improvement analysis and interpretation

In the interpretation phase, LCA users aim to identify the most important aspects of the inventory analysis and the impact assessment. Furthermore, they evaluate the study’s outcomes, do a completeness check, undertake a sensitivity analysis and uncertainty analysis, check for consistency, make conclusions, and recommendations (UNEP, 2003, VanDuinen et al., 2009). The reason for interpreting data are to: firstly, determine the contribution of each component to each environmental outcome; and secondly, evaluate the level of confidence in

the results. Sensitivity analysis was used to determine the effect of each environmental indicator when the inventory data varied ±10%. The uncertainty analysis confirms the absence of any outcome caused by sensitive factors on the findings. The recommendations of the proposed strategies were made in term of the objectives of this research. These included several improvements that would mitigate GHG emissions from the WWTPs. The result was that the power produced from the total GHG emissions exceeded 59% (Zhu, Liu et al., 2013). There is an opportunity to reduce life cycle impacts relating to energy utilisation (Emmerson, Morse et al., 1995, Wu, Meng et al., 2010). The largest proportion of the energy consumption was used in the aeration unit, which accounted for a maximum of 58.8% (Wang, Liu et al., 2012). In contrast low aeration reduces the amount of carbon dioxide emissions but increases the emissions of nitrous oxide (Nguyen et al., 2019). It is necessary to maintain a suitable level of aeration to balance operational efficiency and energy requirements. However, these reviewed studies were limited in the outcomes of the weighting step (Corominas, Larsen et al., 2013).
Most of the LCA studies involved the overall assessment of large wastewater treatment systems. However, regarding GHG emissions, the performance of each treatment unit may lead to different outcomes. Therefore, what is essential here is to propose the best system for the WWTP in term of how each treatment unit operates.

4. Developing strategies based on results of plant-wide models

GHG emissions can be influenced by influent and effluent characteristics and operational conditions (Flores-Alsina, Corominas et al., 2011); it is vital to understand and predict their power generation procedure. Flores-Alsina et al. (2011) demonstrated that GHGs could be quantified during the evaluation of control strategies. Models are useful tools to quantify GHG production and their emissions as well as to evaluate the systems’ performance before implementing them in real-life plants, thus the models serve as an effective solution for control development. Flores-Alsina et al. (2011) suggested using empirical equations and mechanistic models to estimate GHG emissions during the evaluation of WWTP control strategies. The differences between strategies were the quantity of GHG emitted from secondary emission and power consumption sources. This kind of study provides a better picture of overall WWTP performance with a new dimension dealing with emissions. Using simulation in the evaluation process can offer better guidance on the sustainability of different treatment options. Various studies were conducted on the Benchmark Simulation Models (BSM) to explore the influences of some control strategies on several indicators, specifically with reference to their economic and operational aspects.

Some early research demonstrated the quantification of GHG emissions during the evaluation of the control strategies conducted on BSM2 (Corominas et al., 2010) and BSM2G (Flores-Alsina, Corominas et al., 2011). The authors analysed the influence of some operational parameters and identified the strategies to control the emissions. The purpose of these studies were to: (1) consider the change in the influent characteristic and operating conditions; and (2) quantify multi-criteria including effluent quality (EQI), operational costs (OCI), and GHG emissions procedure when comparing the strategies. The results showed that the plant under control could reduce GHG emissions by up to 9.6% (Flores-Alsina, Corominas et al., 2011) and 12% (Corominas, Flores-Alsina et al., 2010). However, when considering other indicators, the scenario with the lowest GHG emissions had the worst EQI due to limited biodegradable organic carbon preventing denitrification. The scenario with the best EQI produced the highest GHGs and proved to be expensive because of the increase in aeration energy.

In fairy recent research, Flores-Alsina et al. (2014) emphasised the importance of multi-criteria evaluation, including GHG emissions when analysing the WWTPs control strategies. The plant under study was simulated by BSM2G. The results showed that the DO set point has a major influence on the plant’s total GHG emissions, the effluent quality and operating cost. Low DO set points resulted in less CO_2 being generated and lower operational costs due to less energy consumption. Also, incomplete nitrification increased the quantity of N_2O emissions, and subsequently the overall GHG emissions increased. This trend was also found in research conducted by Corominas et al. (2010). However, there was a big difference between studies that examined the high DO set point. According to Corominas et al. (2010), at a high DO set point, high energy consumption and incomplete denitrification leads to more emissions of CO_2 and N_2O, respectively. Meanwhile, Guo et al. (2012) indicated that a different DO distribution resulted in different N_2O emissions even at the same energy consumption level. Hence, the influence of DO on GHG emissions should be investigated further.

BSM-e, a modified version of BSM2, was developed to assess control strategies with multiple objectives. The research found a large range of options for mitigating GHG emissions without increasing the operational cost, and also maintaining an acceptable effluent quality (Sweetapple et al., 2014). It is pointed out that to simplify the comparison between strategies, using a single index to present effluent quality is more effective than a focus on specific pollutants. BSM-e includes the modelling of dynamic GHG emissions, but it is unsuitable for achieving multiple objectives due to the high simulation time and the many simulations required (Sweetapple, Fu et al., 2014).

When considering a multi-criteria evaluation, including EQI, OCI and GHG emissions, Barbu et al. (2017) presented a method to enhance the control strategies by adding more control actions. Twelve control strategies were examined from which to choose the best option for these three elements. The best one is the one that controls DO in the fourth tank, nitrate concentration in the last anoxic tank, and ammonium concentration, which refers to the total suspended solids in the last aerobic tank. Santin et al. (2017) researched similar objectives using the same method. Their results showed that the solution for mitigating GHG emissions is to control the dissolved nitrous oxide concentration, ammonium, and ammonia nitrogen concentrations (Santín, Barbu et al., 2017).

Another application of model is to describe the GHG generation mechanism and investigate the effects of operational conditions on the emissions (Boiocchi et al., 2017). Different dynamic simulations were conducted to evaluate the ability to reduce N_2O emissions, which were the smallest in quantity but with the highest global warming potential of all GHG emissions from the WWTP. It is indicated that controlling N_2O emissions will benefit the reduction of total GHG emissions. The model used was the BSM for Nitrous oxide (BSM2N). However, this application could only satisfy one specific aim of N_2O emissions mitigation (Boiocchi et al., 2017).

The plant-wide models make it possible to evaluate the performance of the systems before implementing them in real-life scenarios, thus using the benchmark models are an effective solution for control development. Moreover, plant-wide models can explore the GHG production mechanisms, and the influences of operational conditions. Thus, it is beneficial to use plant-wide models to quantify GHG emissions before controlling them. However, the increase or decrease in consuming resources and recovery leads to different environmental outcomes that are not captured by the simulation model; it is only the LCA that can do this (Arnell, Rahmberg et al., 2017).

5. Integration of LCA and plant-wide models

LCA and plant-wide models have been considered helpful tools to evaluate the environmental impacts and operational condition, respectively. However, when using LCA, the performance evaluation was limited to nitrogen and phosphorus removal. For an optimal overall assessment, models are suggested for use in the LCA research (Corominas, Larsen et al., 2013). It is essential to combine LCA with other indicators so that evaluation is more reliable and accurate; this combination can fill the gap in our knowledge concerning what happens between process control and environmental performance (Flores-Alsina et al., 2010). From Section 3, it can be seen that LCA was applied to assess the impact of some control strategies demonstrated by simulation models. The models were used to measure the quantity of resource inputs and outputs, including GHG emissions, while LCA captured the environmental impacts caused by an increase or decrease inputs and options for recovery. In these situations, the outcomes of LCA could be used for deciding which strategy to use. Once again, plant-wide models are good options to assess the WWTPs' performance.

The integrated LCA and plant-wide models were applied in some studies. Flores-Alsina et al. (2010) first suggested adding the environmental assessment carried out by LCA with economic, technical and legal criteria. The main purpose of their research was to investigate the character and impact of twelve controllers. The evaluation process followed the method of LCA research. Most of the inventory data were collected from the results of the dynamic simulation BSM2. Some other data was adapted from the literature and relevant databases. GHG emissions from treatment processes were not considered in the study, and instead methane and nitrous oxide emissions from sludge were tested for their application to agriculture.

Combination of LCA and another plant-wide model were conducted in a study of Corominas et al. (2013b). They set out to compare the environmental impacts of different controllers. The WWTP layout was simulated with Neptune Simulation Benchmark (NSB) while the direct GHG emissions were estimated using ASM3 Bio-P. The advantage of this research includes the weights, which reflect the relationship of different categories and the results. The main findings were (1) implementing controls for reducing energy consumption is beneficial but does not lead to ideal environmental performance; and (2) nutrient enrichment is the most important factor as it strongly influences selecting the best operational strategies. There are some limitations in the research, such as only the water line was modelled and uncertainty in the N_2O emissions factors was envident. According to the research, significant increasing in the total CO_2 equivalent emissions might result in no change in the final LCA outcomes.

Multiple evaluation criteria for WWTP performance and as environmentally defined by BSM2 jointly with LCA criteria were applied in the study by Meneses et al. (2015). The main objective of their analysis was to compare the environmental profile of the four control strategies implemented by BSM2 from the environmental impact perspective. The impact categories included acidification potential, global warming, eutrophication, photochemical oxidation, depletion of abiotic resources, ozone layer depletion, and terrestrial ecotoxicity. GHG emissions from the biological treatment process were excluded from the study due to the limitations of BSM2. The outcomes of the LCA showed that information on the environmental impacts for each category was evaluated. Since the number of assessed parameters was large, it was difficult to determine the differences and compare them. However, by understanding the relationship of each assessment to obtain the best results, it helps the decision-maker to choose suitable strategy.

According to Arnell et al. (2017), older studies are limited in choosing their boundaries and analysing the operational costs. The dynamic character of GHG production is based on static emission factors that could underestimate the outcomes. The study indicated that it is possible to combine a simulation model and LCA to explore the dynamic effects, operational cost and global environmental impact, including GHG emissions (Arnell, Rahmberg et al., 2017). The goal of their study was to evaluate the change in environmental impacts from the different strategies where the same effluent quality was assumed. Findings showed that adding chemically enhanced primary treatment reduced the volume of total direct GHG emissions due to the significant reduction of N_2O emitted from the activated sludge unit. The limitation of this research is that the weighting step was not undertaken, but nonetheless it pointed out that combining the simulation model and LCA can both describe the processes, and evaluate the environmental impact (Arnell, Rahmberg et al., 2017).

6. Discussion and future research

6.1. Discussion on combined LCA and plant-wide models

LCA and plant-wide models are widely used in assessing different WWTPs' treatment strategies. However, when considering GHG emissions from WWTPs, each type still has some disadvantages due to the complex treatment processes and environmental conditions. For studies conducted with LCA only, the overall environmental impacts were analysed but evaluation was lacking for operation cost, technical issues and effluent standards. The optimisation of treatment technologies dealing with nitrogen and phosphorus removal has never been evaluated through LCA due to technical difficulty of assessing multiple strategies at full-scale WWTPs. It can be seen from Section 3 that there are few in number of research considers GHG as the main indicator for assessing the WWTPs' performance.

Furthermore, CO_2 from the biological process is usually neglected while N_2O, CH_4 emissions are normally collected from the sludge treatment process only. Lack of this kind of information leads to insufficient data for building the control framework, and consequently affects the performance of the WWTPs. The quantification of GHG emissions from BNR systems is uncertain. The usual way to estimate GHG emissions is based on IPCC guidelines. Proposed strategies by LCA give the options to reduce the quantity of GHG emissions, but the input data is mostly based on the literature while the uncertainty range correlates with the number of input data. Hence, it is vital to create a complete and reliable database to improve the overall quality of LCA.

The following research questions were developed by reviewing these LCA studies:

(1) Which processes of wastewater treatment (inside/ outside the WWTPs) are assessed?
(2) Which type of effects are considered?
(3) Which specific LCA methods are applied?
(4) How are GHG emissions quantified?

Exiting studies with plant-wide models have their limitations due to the outcomes of the control strategies selected to give the best effluent quality which may increase GHG emissions. Benchmark simulations are used for effluent quality indicator and operational cost indicators while a potential environmental assessment is not considered. According to the study by Barbu et al. (2017b), when evaluating multiple criteria, each controller achieves goods results in one of the indicators, but it has a different impact on the others. Moreover, sometimes increasing or reducing the input/output may not lead to any change in total environmental impact, which only is captured by LCA (Arnell, Rahmberg et al., 2017).

The combination of plant-wide models and LCA results represents an innovation in the environmental evaluation of WWTPs' operations (Meneses, Concepción et al., 2015). Simulating the performance criteria on plant-wide models complements the environmental evaluation based on LCA and offers a better overall assessment of WWTPs as can be seen in Table 2. Barbu et al. (2017b) emphasised the importance of analysing the LCA contribution in order to get a broader view of the environmental consequences. With LCA, it is possible to add extra criteria that complement the evaluation criteria provided by plant-wide models.

Table 2. Variables in each analysis methods

Method(s)	Input	Output	Local/ regional/ global impacts	Boundary
LCA	Electrical energy Resource consumption for water treatment	Abiotic depletion Eutrophication Global warming Acidification Human toxicity	Include	Construction Operation Maintenance Demolition

	Resource consumption for transport			
Plant-wide models	Electricity Chemical Fuel oil Flow rate Influent characteristics	GHG Effluent Operating cost	Exclude	Operation
LCA + plant-wide models	Electrical energy Resource consumption for water treatment Resource consumption for transport Flow rate Influent characteristics	GHG Effluent Operating cost Environmental impacts	Include	Construction Operation Maintenance Demolition

Judging by the results of existing studies, it is evident that multi-criteria evaluation is possible but complex. The simulation models make it possible to describe the process in detail while LCA helps to evaluate the overall outcomes, including the side effects and reflexion effects. Plant-wide models capture both direct and indirect GHG emissions from electricity and chemical consumption. When comparing the strategies, numerous indicators were involved, and their influences with other assessments at different levels were explored by conducting sensitivity analysis in LCAI. The combination of LCA and plant-wide models provide information on the environmental impacts for each impact category (Meneses, Concepción et al., 2015). It helps the policy or operations decision-makers choose the best strategy. LCA when combined with plant-wide models gives more realistic information than steady state assessments (Bisinella de Faria et al., 2015).

When evaluating the control strategies, plant-wide models look at the working scenarios while LCA focus on the total environmental impacts. The simulation platform consists of a plant layout, sub-models for water line and sludge line, a model for controllers, and influent profile (Arnell, Rahmberg et al., 2017). The simulation model is conducted for the on-site processes by providing a list of material, energy and other resouces; then the semi-outputs include solid discharge, GHG emissions and effluent are measured. That information will be used as input to calculate the potential effects on human health, the availability of resouces, and the natural environment in LCAI as presented in Figure 4. Base on these steps, the influence of different input elements will present variety in environmental impacts.

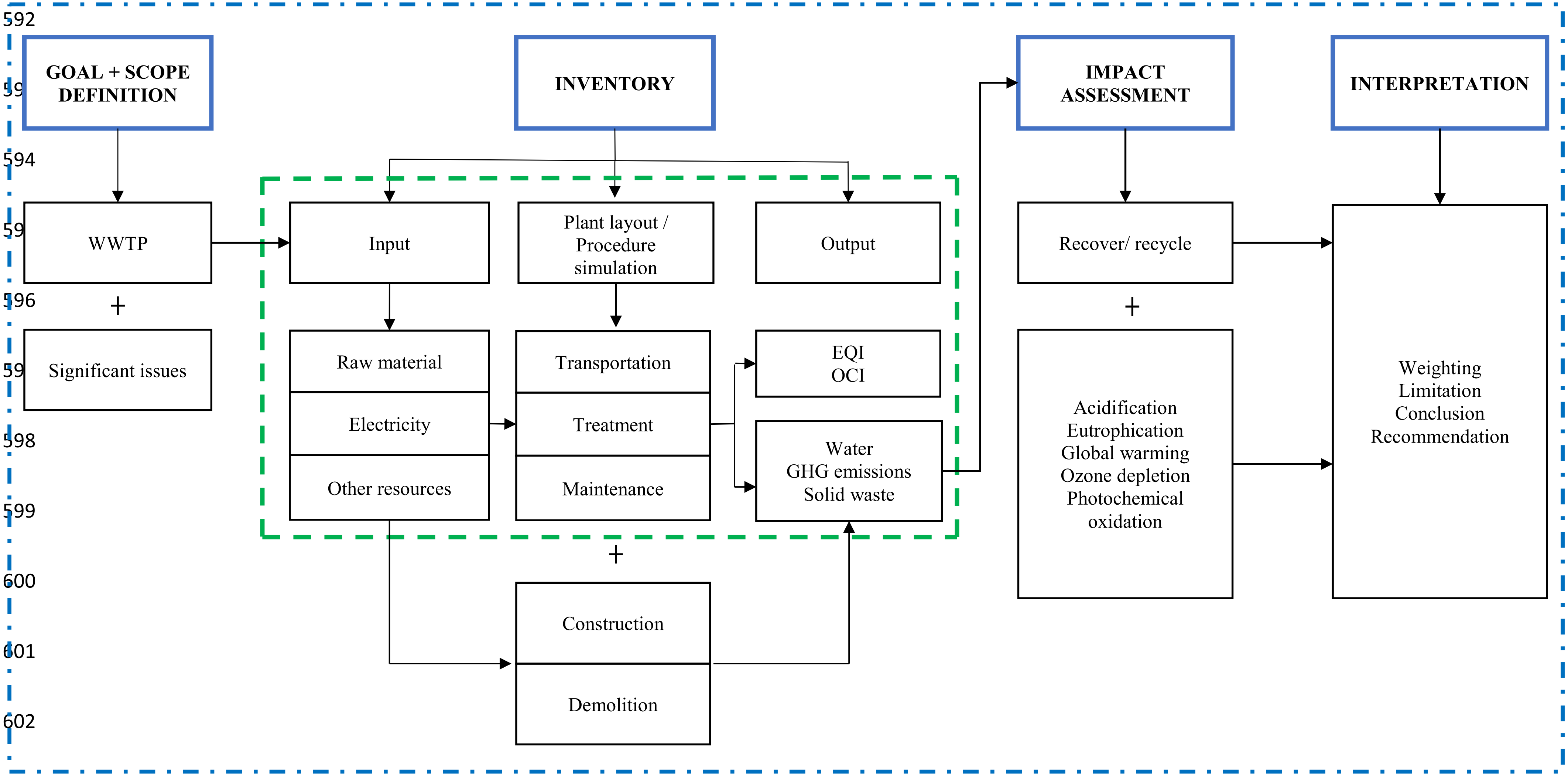

Figure 4. Frame work of the combination between LCA and plant-wide models.

Boundary of plant-wide models

Boundary of LCA

Existing research has encountered some uncertainties as follows. The simulation models could not assess the full dynamics of N_2O production and emissions based on real data (Mannina, Rebouças et al., 2019). The trajectory and relationships between impact categories were studied in reviewed articles. However, it is difficult to compare values between studies due to differences in choosing boundaries, functional units, impact categories, and specific scopes. The best control strategy is the one that can balance EQI, OCI, GHG emissions, and results in environmental impacts on all categories.

6.2.Future research

Due to the limitations of this combination, there are two main things that need to be considered. (1) Weighting step helps to evaluate different impact categories, which is vital for decision-making. The role of weighting is to explore the level of potential impacts in different impact categories. Existing articles studied the relationship between EQI, OCI, GHG emissions and total environmental impacts. However, using a general weighting factor equal for all impact categories makes the weighting process more complex and difficult to balance. There is a need to determine the suitable weighting factor for sensitivity analysis when combining LCA and plant-wide models. (2) The current challenge in mitigating GHG is the lack of information about N_2O generation and emissions from treatment processes. Although the volume of N_2O produced in WWTP is smaller than CO_2 and CH_4, its GWP is 9.5 times higher than methane and 265 times higher than carbon dioxide (IPCC, 2014). A comprehensive model that is able to include all the mechanism related to N_2O formation is critical for understanding the nature of GHG emissions and how to manage them better.

7. Conclusion

WWTPs are complex operational processes that consist of transportation, treatment, and resources consumption. Regarding the overall performance of a WWTP, four aims need to be considered and balanced when proposing the control strategy: (1) mitigate the pollutant discharge including GHG emissions; (2) ensure the quality of effluent ; (3) maintain costs for the lifetime of a WWTP; and (4) minimise the global environmental impact. Evaluating strategies is a difficult task regarding the number of parameters and variables that can affect the results at different levels. This paper has presented a comprehensive overview of the integrated plant-wide models and LCA. The use of models coupled with LCA to develop the analytical framework provides a more complete evaluation and more detailed description than a single method could. When these two methods are combined, WWTPs can achieve very efficient performance with minimal environmental impacts.

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