processes

MDPI

Review

Life Cycle Assessment and Its Application in Wastewater Treatment: A Brief Overview

Siti Safirah Rashid [1,*], Siti Norliyana Harun [2,*], Marlia M. Hanafiah [2,3], Khalisah K. Razman [3], Yong-Qiang Liu [4] and Duratul Ain Tholibon [1]

1 School of Civil Engineering, College of Engineering, Universiti Teknologi MARA (Pahang), Bandar Tun Abdul Razak 26400, Pahang, Malaysia
2 Centre for Tropical Climate Change System, Institute of Climate Change, Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia
3 Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia
4 Faculty of Engineering and Physical Sciences, University of Southampton, Southampton SO17 1BJ, UK
* Correspondence: sitisafirah@uitm.edu.my (S.S.R.); sitinorliyana@ukm.edu.my (S.N.H.)

Abstract: This paper provides a brief review on wastewater treatment system and the application of life cycle assessment (LCA) for assessing its environmental performance. An extensive review regarding the geographical relevance of LCA for WWTPs, and the evaluation of sustainable wastewater treatment by LCA in both developed and developing countries are also discussed. The objective of the review is to identify knowledge gap, for the improvement of the LCA application and methodology to WWTPs. A total of 35 published articles related to wastewater treatment (WWT) and LCA from international scientific journals were studied thoroughly and summarised from 2006 to 2022. This review found that there is lack of studies concerning LCA of WWTPs that consider specific local criteria especially in the developing countries. Thus, it is important to: (1) assess the influence of seasonality (i.e., dry and wet seasons) on the environmental impact of WWT, (2) investigate environmental impacts from WWTPs in developing countries focusing on the site-specific inventory data, and (3) evaluate environmental sustainability of different processes for upgrading the wastewater treatment system. The environmental impact and cost assessment aspects are crucial for the sustainable development of WWTP. Therefore, environmental impacts must be thoroughly assessed to provide recommendation for future policy and for the water industry in determining environmental trade-offs toward sustainable development.

Keywords: life cycle assessment; wastewater treatment plant; sustainability; environmental impact

Citation: Rashid, S.S.; Harun, S.N.; Hanafiah, M.M.; Razman, K.K.; Liu, Y.-Q.; Tholibon, D.A. Life Cycle Assessment and Its Application in Wastewater Treatment: A Brief Overview. *Processes* **2023**, *11*, 208. https://doi.org/10.3390/pr11010208

Academic Editors: Dimitris Zagklis and Georgios Bampos

Received: 8 November 2022
Revised: 29 November 2022
Accepted: 9 December 2022
Published: 9 January 2023

1. Municipal Wastewater Treatment System

A municipal wastewater treatment system is encompassed of a sewer system and wastewater treatment plant (WWTP) and characterized by Sikosana et al. [1] as the most common sort of wastewater belonging to the low-strength waste stream category. There are two types of sewer system connected to WWTP: (i) separate sewer system with different flow/network for rainwater runoff and domestic/industrial wastewater, and (ii) combined sewer system of the same sewer pipe for both rainwater runoff and domestic/industrial wastewater. A WWTP consists of different processes or operating units (e.g., pre-treatment, primary treatment, secondary treatment, sludge treatment and tertiary treatment) as shown in Figure 1. Pre-treatment and primary treatment are mainly focused on removal of particulate pollutants such as solids, grit, and greases. Secondary treatment treats organic matter, nitrogen, and phosphorus contained in the sewage through biological and chemical processes [2–4]. Tertiary treatment is applied to remove remaining small particles and pathogens in some WWTPs.

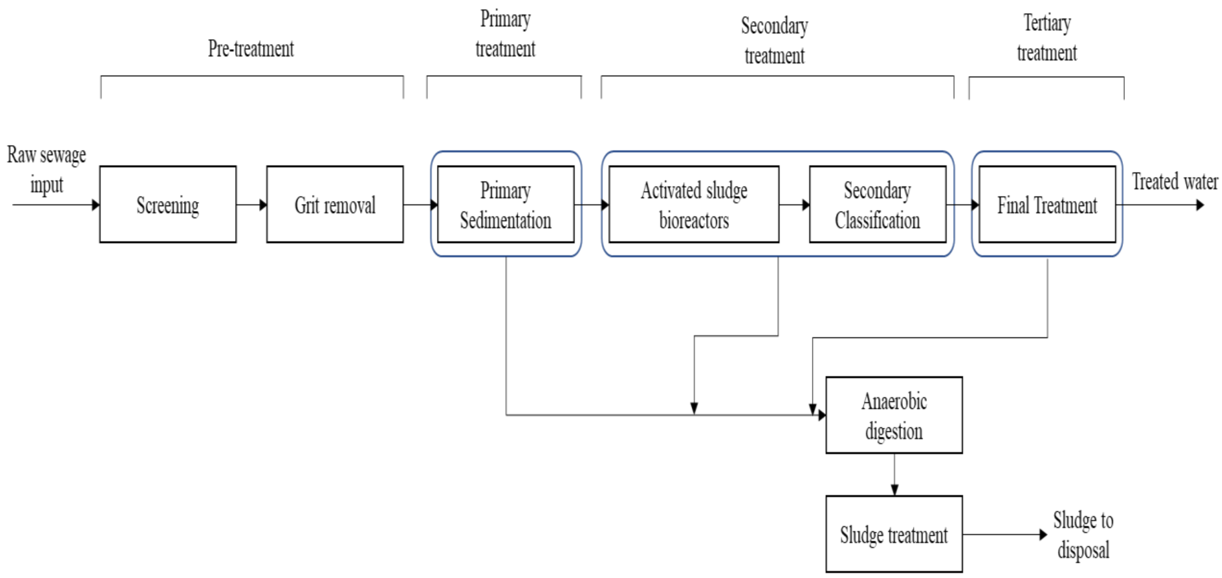

Figure 1. Flow diagram of the WWTP process.

Finally, sludge treatment treats the excess sludge for stabilisation and volume reduction through sludge thickening and dewatering. The sludge is sent to landfill, used in agriculture, incinerated, or transported to composting plant. Meanwhile, constructing a WWTP is a challenging process that implicates various types of materials such as concrete, timber, steel, and plastics, and involves detail operational design and equipment. The operation of WWTP requires: (i) a large amount of electricity for pumping or aeration, (ii) chemicals for sludge treatment and phosphorus removal, and (iii) transportation of waste, sludge, and chemicals [5]. Consequently, WWTP has substantial environmental impacts during its life cycle (i.e., construction, operation, and demolition) due to the energy consumption, chemical usage, sludge generation, effluent discharge, and gas emissions [6].

2. The State-of-the-Art Methods for Applying LCA in Wastewater Treatment Plants

Over the last 50 years, an increased awareness has developed in global society about protecting the environment particularly water resources. In relation to that, the European Commission Council Directive (1991/271/EEC) concerning urban wastewater treatment stated that the objective of wastewater treatment is to protect the environment from adverse effects of discharging urban and industrial wastewater. A large number of wastewater treatment plants (WWTPs) are designed and operated to prevent pollution to the environment by removing a variety of contaminants from wastewater before discharge, restoring desirable quality to water that has been contaminated by humans or nature [7].

However, to some extent, the pollutants in wastewater could be transferred to air such as greenhouse gases (GHGs) emissions [8,9] and soil such as disposal of sludge due to wastewater treatment, which could lead to negative effects on human health and the environment in other forms. This holistic environmental impact from WWTPs is very challenging to evaluate, and thus, a cradle-to-grave approach is needed to analyse the consequences of these plants to the environment. Some environmental impacts from the operation of WWTPs include climate change from the emission of GHGs, eutrophication from the emission of nutrients to the water body, and ecosystem damage from the emission of heavy metals, with the United Nation's sustainable development goals addressing climate change, eutrophication, and acidification of water bodies as the most pressing impacts. Therefore, conducting an environmental impact assessment for particular technologies, products or processes is very important to identify their environmental impacts and potential mitigation strategies.

The application of environmental assessment tools provides reliable environmental impact information that assists in decision-making toward sustainable operation of a system or process [10]. At present, the impact of a wastewater treatment system can be assessed through different evaluation tools such as the LCA method, economic and exergy analysis, the environmental impact assessment (EIA) method, and net environmental benefit analysis (NEBA) [8]. LCA is an approach in assessing the environmental impact associated with all stages in the life cycle of commercial products, processes, or services, and according to Nizam et al. [3] should be assessed in order to create environmentally acceptable technology for future development. In LCA, environmental impacts are assessed from raw material extraction of the product or process to the final disposal of the materials, i.e., cradle to grave [3,8].

The use of LCA has started to draw great attention of many researchers and industrial practice in identifying environmental impacts and evaluating the sustainability of wastewater treatment/technology selection [6,11,12]. This is because LCA provides a complete framework of assessment starting from the goal and scope (objective), life cycle inventory, life cycle impact assessment, and interpretation. Meanwhile, an economic analysis could be assessed using cost-benefit analysis (CBA), life cycle costing (LCC), and techno-economic analysis (TEA) [13–15]. Usually, this economic evaluation can be combined with LCA to produce a robust evaluation for a system-level analysis towards the sustainable operation of WWTPs.

Compared with LCA analysis for the manufacturing sector, an LCA of wastewater treatment is fairly established with about 20 years of practice. Since 1995, more than 70 international peer-reviewed articles dealing with WWT and LCA have been published with different inventories, boundary conditions, functional units (FU), and impact assessment methods. The various research papers have shown that LCA has evolved in the past two decades to include more improvement and systematic assessment. An extensive review of existing LCA studies was conducted for this research to assess the state-of-the-art knowledge on the environmental impact and benefit of LCA to identify the knowledge gap. Based on the selection of related journals, 60 published articles were found to be related to WWT and LCA from the international scientific journals reviewed, but only 58% of the papers published from 2006 to 2022 (Figure 2) were selected and summarised. The criteria of searched for the published articles was based on the topic of 'Life Cycle Assessment' and 'Wastewater Management and Treatment' for various countries to analyse various studies conducted on this topic.

A LCA is an approach that considers environmental, economic, and social impacts that a product or service will produce throughout its life cycle. A life cycle sustainability assessment (LCSA) considers the environmental, economic, and social ramifications of a product's whole life cycle, i.e., from "cradle to grave," as well as its use and waste disposal [16]. It can be used as a technical tool to identify opportunities to reduce the environmental effects associated with a specific product, system, material or activity through consideration of the burdens during manufacturing and as a finished product [17]. LCA has been applied in various research settings to analyse the environmental impacts of different WWTPs as they have a significant environmental impact on receiving water bodies and cost municipalities or industrial facilities a lot of money [18]. However, the scope of assessment is rather challenging due to the variation in defining the system boundaries and the difficulty in considering wastewater composition and the type of pollutants. Different options of wastewater treatment technology have different performances and impacts on the environment, which may take place during different phases in a WWTP's life cycle. In the following overview, relevant studies within this field of research are briefly described mainly to provide a benchmark of LCA methodology application in the wastewater treatment.

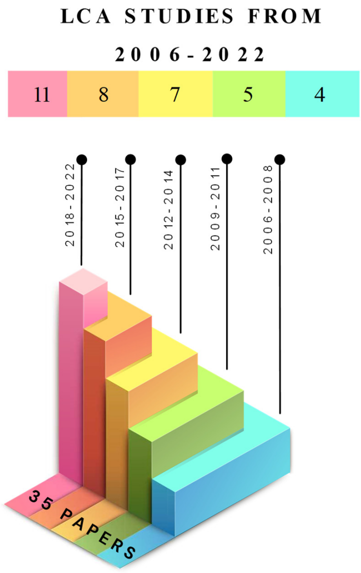

Figure 2. Number of LCA studies from 2006–2022.

Based on the detailed review discussed in Section 7, published research on the LCA of wastewater treatment can be classified into two types. One type focuses on using LCA to facilitate technology comparison and selection from the environmental impact point of view. The other type focuses on working on different steps of the LCA method itself (i.e., goal and scope, inventory, impact assessment, and interpretation) to improve the reliability of the LCA results. Some researchers have even developed new models for the calculation of new characterisation factors or new impact categories, such as a new characterisation factor for pollutants or substances to provide more representative and reliable analysis. For instance, one study conducted an environmental evaluation of common technical options for urban wastewater treatment [19], whereas another identified the overall environmental impact of WWTPs (for both water and sludge treatment) using LCA methodology [20]. Some studies have also conducted specific evaluations of GHG emissions from WWTPs [21–23], including one environmental–economic evaluation of the sludge treatment process in Korea that used life cycle analysis [6].

In more detail, LCA methodology was also used by Ontiveros and Campanella [24] to evaluate the environmental performance of three different advanced biological nutrient removal processes in Argentina: modified UCT, five stages Bardenpho, and modified Bardenpho from WWTPs. This evaluation can guide the selection of the biological nutrient removal process in the Argentina context from both technological and environmental points of views. In a different aspect, Yoshida et al. [25] conducted a study on the improvement of life cycle inventory and methodology involving the consideration of onsite GHG emissions and long-term emission data in the land application of sewage sludge. In addition, Morera et al. [5] worked on the improvement of LCA methodology in the urban wastewater treatment system and emphasized the improvement of construction detailed inventory including sewer system and inventory improvement with scale assessment. Recent research identified that most studies using LCA for WWTPs aim to evaluate the environmental impact of different technologies including identifying advanced and conventional emission parameters [26,27], analysing control strategies of WWTP performance [12] and identifying the environmental trade-off of different process alternatives. These findings showed that LCA can assess various aspects of identifying environmental impact from wastewater treatment but the methodology from the framework provided by the International Standard Organisation (ISO) could be further improved. The social factor is more complicated and is not included in this review.

A review of 35 published LCA studies of WWTPs (from 2006 to 2022) identified that most of the published studies have been concentrated in the European continent, followed by the Asian continent, mainly contributed by China with little application from other developing countries such as Thailand and Malaysia (Figure 3). In terms of technology coverage, only a few studies have applied LCA to resource recovery, especially in developing countries. The analysis in these 35 papers also revealed that there is variability in the definition of the functional unit (FU) and the system boundaries, the selection of the life cycle inventory and impact assessment methodology, and the procedure results interpretation. As supported by Hauschild et al. [28], the LCA standard of ISO 14040 is still general and unspecific in its requirement. Besides that, there is a scarcity of secondary data which is commonly obtained from published data of LCA studies, and the data may be incomplete [29,30]. Therefore, there is a need to investigate the standardized guidelines for the wastewater treatment operation by evaluating the key steps in the LCA methodology to improve the quality of LCA–WWTP.

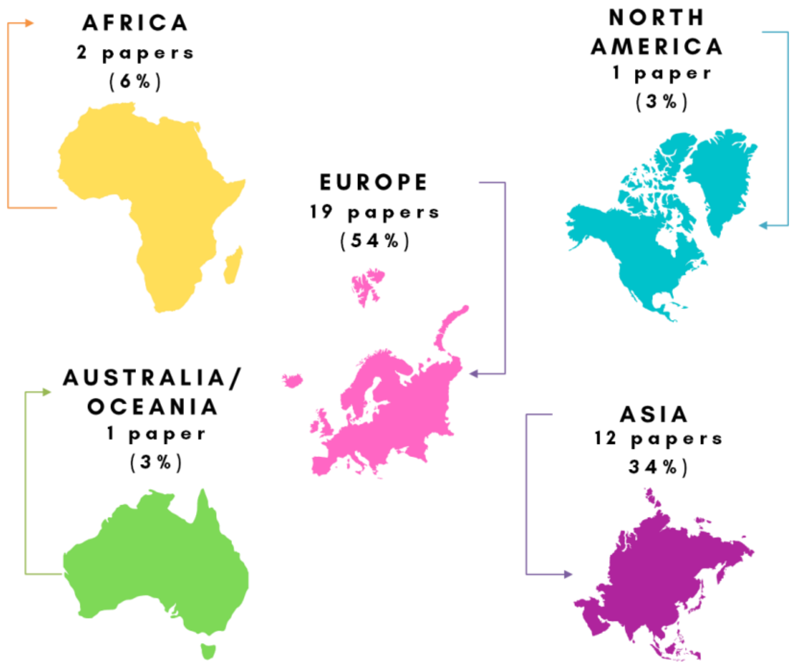

Figure 3. LCA studies based on their continents.

3. Key Steps for LCA Assessment

LCA is a standardised methodology to evaluate the environmental impacts associated with a product or process during its complete life cycle as described in two ISO norms, ISO 14040 and 14044 [31]. The concept of LCA first emerged in the late 1960s. In the 1970s, LCA only focused on energy and raw materials, but later the analysis system expanded to emissions, water, air, and soil. Starting in the 1990s, LCA was applied in wastewater treatment after being identified as suitable for related environmental assessments. In 1994, the ISO began developing standards for the LCA method as part of its 14,000 series on environmental management; however, the method was not yet designed in detail for all fields of assessment [32]. Nevertheless, since then more studies on LCA have been undertaken and published in various disciplines, including a variety of boundary conditions, databases, impact assessment methods, and interpretations.

Several software programs have been developed including free and commercial software to assist in the analysis of LCA. At present, various types of commercial LCA software are available such as SimaPro, Gabi, Umberto and, openLCA [33,34]. SimaPro was developed by Pre-Sustainability Consultants in the Netherlands and has been used for more than 20 years in various studies and projects. It is a user-friendly tool that helps to model and analyse complex products or systems such as water and wastewater treatment. It can also calculate environmental impacts and detect environmental hotspots in a systematic way [5].

In addition, OpenLCA, developed in Germany, is another free software for LCA user [24]. All of these programs are professional life cycle modelling tools and available with various embedded databases such as Ecoinvent, European Life Cycle Database (ELCD), and U.S. Life Cycle Inventory (USLCI). However, one of the challenges of LCA is that it requires detailed inventory information for each system assessed [35].

A detailed review on LCA methodology steps was conducted to understand more about the application of LCA. The structured methodology in LCA as stated in ISO starts with defining the goal and scope followed by life cycle inventory (LCI), and life cycle impact assessment (LCIA), and ends with a results interpretation as shown in Figure 4. This methodology highlights the general steps or flow of LCA with general characteristics that have been identified within each step.

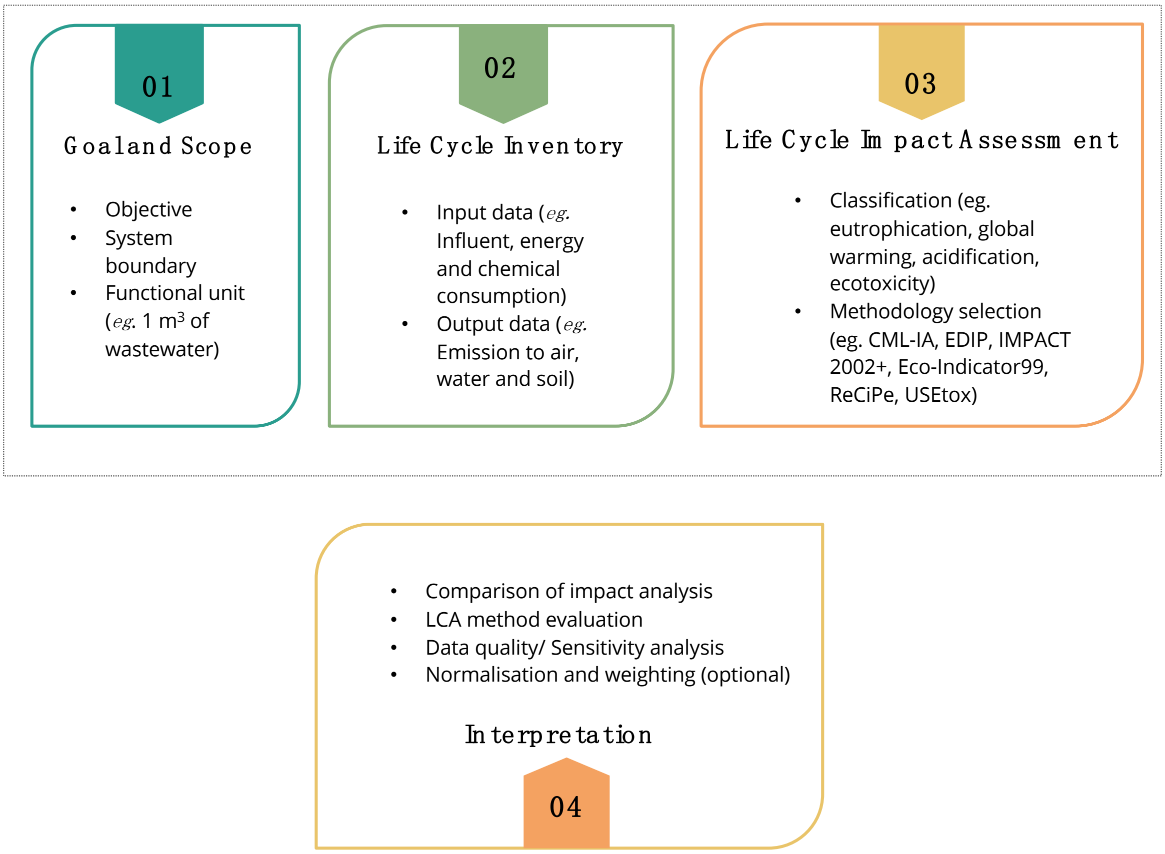

Figure 4. LCA methodology steps for environmental impact assessment from WWTPs.

3.1. Goal and Scope

In detail, the goal and scope of LCA consist of the objectives, system boundary, and functional unit. The objectives consist of the environmental analysis, the technology comparison, and their effect on the environment or the analysis of life cycle inventory and methodology to various impact categories. The system boundary determines which unit process shall be included in LCA analysis [31] such as construction stage, operation, sludge treatment and disposal, and demolition phase. As shown in Figure 5, all of the studies covered operation since it contributes to the highest to the total environmental impact [12,33,36] with merely 7% of the studies analysing the phases of construction up to its disposal/demolition. Lorenzo-Toja et al. [37] reported that the environmental impact from the construction phase is almost negligible for many impact categories compared with the operational phase.

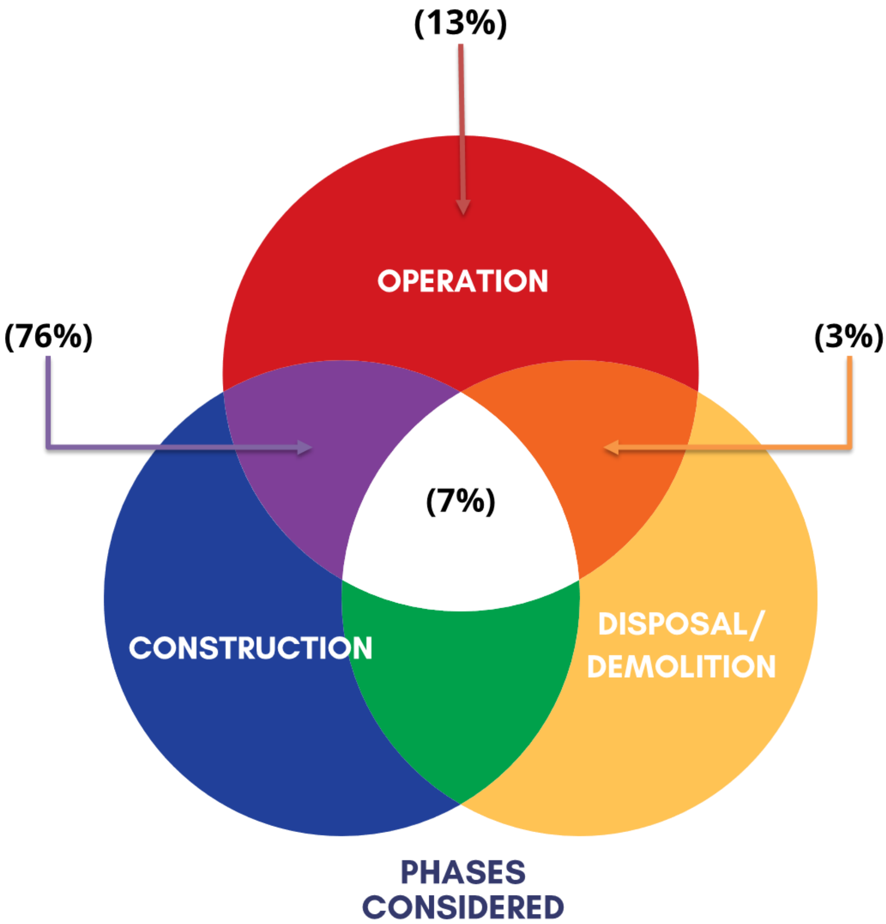

Figure 5. Phases of processes considered for the LCA.

Similarly, Pasqualino et al. [20] stated that the environmental impact from the construction and demolition phases also could be considered negligible. In the operational phase, approximately 80% of the studies included sludge treatment and disposal in the system boundary due to the importance of this stage to the overall impact [32]. Finally, the functional unit is usually defined as the treatment of a volume of wastewater in 1 m^3; however, some studies have used population equivalents (PE/year). In addition, several other options are available for the functional unit in LCA–WWTP such as the quantity of sludge produced and the quantity of removed pollutants [38]. However, no strong justification appears to exist between its selection and technologies used in a specific system of WWT. To analyse this issue, Rodriguez-Garcia et al. [39] studied the effect of a functional unit based on wastewater volume (m^3) to identify the different effluent quality of six typologies of WWTPs. They found that global warming and economic cost decrease following better eutrophication.

By contrast, studies with similar FU found that a trade-off exists between lower eutrophication, higher environmental, and economic impact when involving more demanding/upgrading treatment such as water reuse. These conflicting results show that discrepancies still exist when using single FU to identify the effect of different treatment technologies. Therefore, Rodriguez-Garcia et al. [39] have suggested that a second FU should be introduced in specific studies such as those on eutrophication reduction (kg PO_4^{3-}) to overcome this limitation and strengthen the system under study. This suggestion was supported by Corominas et al. [32] who determined that a FU of a system could influence the final result, especially when comparing WWTPs with different influent qualities or different removal rates.

3.2. Life Cycle Inventory

After the goal and scope are determined, the second step in a LCA is data collection and inventory build-up, a crucial stage when performing an LCA study. In general, life cycle inventory (LCI) aims to identify the inputs (resources), the outputs (effluent and waste), and the respective amounts of emissions over the entire life cycle of the specific process. Generally, it is given in physical units such as kilogram (kg), cubic metre (m^3), and kilowatt–hour (kWh). Wastewater treatment data inventory includes the foreground as the primary data (operation), which is usually compiled from the operational record, detailed design document, sampling works, and vendor-supplied information. By contrast, background data (secondary input) such as energy production and chemical production are normally provided by the LCI database (e.g., the Ecoinvent and the ELCD). Ecoinvent, which was developed by the Ecoinvent Centre in Switzerland, is one of the major data inventory providers used in various sectors. In the LCI phase, identified inventories are collected for all processes of the boundary and calculated to the same functional unit.

3.3. Life Cycle Impact Assessment

Prior to the calculation of the environmental impacts, the assessment methodology must be selected to give direction to the category of impact required, such as the midpoint level or the endpoint level. Several different methodologies are available to identify related impact categories in the LCA such as Eco-Indicator99 [33], Recipe [36], EDIP 2003, USEtox, IMPACT2002+, and CML2001 [40]. CML2001 is found to be the highest number in the methodology used by researchers due to its extensive impact categories, high relevance to wastewater treatment at the midpoint level, and accurate results as shown from a previous study [20]. For the life cycle impact assessment (LCIA) phase in every method, the inventory data (LCI) emitted to air, water, and soil compartments are multiplied with their characterisation factor (CF) to convert to environmental impacts in various categories, as shown in Equation (1) [41].

$$\begin{aligned} &\text{LCIA} = \text{LCI} \times \text{CF} \\ &\text{E.g. Freshwater Ecotoxicity Potential (FEP)} = \\ &(\text{LCIair} \times \text{CFair}) + (\text{LCIwater} \times \text{CFwater}) + (\text{LCIsoil} \times \text{CFsoil}) \text{ (unit: kg1,4-dBeq.)} \end{aligned} \tag{1}$$

Characterisation factors (CFs) of inventory data or pollutants are provided to practitioners either in the literature or by the software used [42]. CF models are built based on the mechanism of the cause–effect chain starting from the emission of pollutants until the receiving compartments. CF values are the total results of environmental fate, exposure, and the resulting effect on the exposed section such as human [43]. CFs were calculated by multiplying fate factor (FF) to exposure factor (XF) and effect factor (EF). Fate factor (FF) denotes the residence time of the substances/pollutants in the receiving compartments. Exposure factor (XF) relates to the actual concentration of substances taken by the receiving compartment, e.g., human. Effect factor (EF) is correlated to the route of exposure, e.g., ingestion and inhalation effect to human toxicity. Exposure factor and fate factor are combined to form the intake factor (IF) of a substance [44].

Nevertheless, various discrepancies still exist between methods provided in LCA. To address this issue, Pizzol et al. [45] compared nine different methodologies focusing on the impact of metals on human health. The results showed a poor agreement between the methods. For example, the contribution of metal to total human health changed greatly between the methods. This poor agreement is due to the different types of metal considered and the different techniques used to calculate the characterisation factor. This indicates that there is no unified LCIA method, especially for the human health impact category. Table 1 lists the origin or provider of each methodology provided in LCA.

Table 1. List of environmental impact assessment methods.

Method	Developer
CML 1992/CML-IA	Centre for Environmental Studies, University of Leiden
Eco-indicator 95/99	Pre Consultant B.V
Eco-points 97	Swiss ministry of the environment
EDIP 2003	Institute for product development (IPU) at the Technical University of Denmark
IMPACT 2002+	Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland

Midpoint environmental impact categories are provided in each method. For example, in CML-IA, the midpoint categories involving wastewater treatment normally include abiotic depletion (fossil fuel), eutrophication, global warming, acidification, ozone depletion, and human toxicity potentials. However, water, land, and energy use have been increasingly gaining attention in this research area as new impact categories, depending on the objective of the study. In contrast to midpoint categories, the endpoint damage category is always considered in the LCA assessment as an endpoint area of protection. The categories include damages to human health, ecosystems, and resource availability.

3.4. Interpretation

The final stage of LCA methodology is interpretation. This final stage can identify and evaluate information from the result of the life cycle impact assessment because it can determine the level of confidence in the final results. It starts with an understanding of the accuracy of the result and how it meets the goal of the study. According to Corominas et al. [32] and based on the ISO 14040:2006, the interpretation part in the LCA includes: (a) identification of important issues based on the results of the LCI and LCIA; (b) evaluation of the study considering completeness, sensitivity, and consistency checks; and (c) conclusions, limitations, and recommendations.

4. Geographical Relevance of LCA for WWTPs

Before the 2000s, the majority of the traditional LCA approach was based on site-independence where no consideration was given to geographical and temporal factors. The reviewed study showed that some published papers used secondary data (e.g., from literature) or simulated data to conduct LCA analysis due to the lack of the available primary data, leading to much less reliable results. However, the results still could provide some guidance to a certain degree. For the inventory practice, approximately 55% of studies for LCA–WWTP were based on site operation while others still depended on the estimations, existing simulation data, previous reports, and literature due to the limited availability of reliable databases. The other reason was that performing onsite measurements that obviously can reduce the data uncertainty is often not feasible as the process is expensive and time-consuming.

The analysis of the geographical distribution in LCA found that only a few studies were conducted in developing countries such as India, Egypt, Thailand, and Malaysia. As a consequence, the distributions of studies with regard to the assessed wastewater management systems by LCA on environmental concerns are specific to a few regions only. The drawback of this analysis system is that another country in a different region with a different temperature or economic value cannot meaningfully refer to the existing available data and impact results. This situation shows that the fairly distributed databases around the world are still lacking in LCA analysis studies for WWTPs, especially in developing countries. This idea was supported by Renou et al. [46] who reported that location-specific factors are critical especially for eutrophication and terrestrial ecotoxicity impact category due to the transportation effect by pollutants. Therefore, the selection of inventory data is critical to LCA analysis especially when local factors such as dry and wet season are accounted in the analysis to provide reliable results.

To overcome this limitation, there was a trend after 2000 towards making LCA more site-dependent, considering more site-specific characterization factors such as eutrophication, toxicity impact, and acidification potentials. This is because the point of emission may have a strong impact on these regional and local impact categories. For global warming and ozone layer depletion, characterization factors are justifiable because the emission location has no influence on the transportation effect [47]. Therefore, it is important to identify specific characterisation factors that impact the different countries that have different geographical, climatic, and economic factors, which are significantly lacking in developing countries. This brings into question how the importance of regionalisation criteria and the database influence the LCA results.

Therefore, there is still some possibility that the LCA method for wastewater treatment impact assessments can be improved, especially outside of Europe with consideration for the variability of treatment technology. For example, Yoshida et al. [25] studied the effects of three different inventory databases to the LCA results that are from the European Pollution Release and Transfer Registry (EPRTR), the Denmark national discharge limit data and data collection scheme conducted at the WWTP in Copenhagen, Denmark. They found that the LCA results depended heavily on the onsite data input. For instance, the EPRTR did not capture impact for particulate matter and terrestrial eutrophication. They found that primary data (i.e., site data collection scheme) from WWTPs gave the most reliable LCA results but still needed some improvements, such as the expansion of substance coverage and additional detail collection of energy and chemical usage. On the other hand, for the temporal effect, even though Lorenzo-Toja et al. [37] and Alfonsín et al. [27] identified no clear difference in environmental performance between WWTPs from the Atlantic and Mediterranean regions of Spain, the effectiveness of using the existing secondary databases in a different region, especially in a different climate of a developing country, is uncertain. Therefore, it is well proved that site-specific inventory data is the key to obtaining reliable LCA results.

The review in this chapter shows that research focused on specific local conditions and inventory effects to the LCA results have been rarely assessed in LCA–WWTP related studies. Most of the studies also did not stress the importance of geographically different impacts in terms of data inventory and local factors (e.g., temperature and rainfall). In fact, some of the research outside of Europe uses European datasets for its region without adjusting for uncertain information such as the local impact factors of electricity. One of these factors is the availability of a generic database, which decreases the need for the importance of local primary data. Furthermore, most of the characterisation and normalisation factors are also based on European conditions, where these factors are currently used globally only due to their availability.

However, very few studies have been conducted using LCA in developing countries. The lack of primary data and underrepresentation of the life cycle thinking concepts in developing countries are possibly the main causes for the restricted number of studies published. In the wastewater sector, besides energy and chemical production data, the most important aspects are the effects of temperature, rainfall intensity, local pollutants, and design criteria (e.g., combined or separate sewer systems), all of which could be included and analysed. Moreover, the impact of treatment technology is greatly dependent on the local situation/factors such as geographic location, wastewater characteristic, energy type and source, choices of sludge and waste disposal options, and size of markets for products derived from WWT system such as fertiliser.

The review in this chapter suggests that it is important to have inputs based on a localised primary and secondary database with regard to local characteristic representing specific region such as tropical developing regions or Europe. In other words, the new localised database can keep the commercial data inventory as a benchmark. For example, Europe has a temperate climate (i.e., warm in summer and cold in winter) while tropical zones having warm weather year-round. Indeed, regionalisation is recognised as an important step towards improving the accuracy, precision, and confidence in LCA results.

5. Benefits of LCA for Environmental Impact Evaluation of WWTPs

The current LCA is well described in terms of the framework and can be applied to a wide range of products including waste and water cycles. Therefore, in this situation, LCA could be a tool to identify environmental factors and assess impacts from the wastewater treatment operation [12,24]. Furthermore, Foley et al. [48] pointed out that while their research had provided new inventory data needed about WWTPs, without life cycle impact assessment modelling they could only identify a limited comparison for the impacts by the newly provided data.

Besides identifying the environmental impacts from WWTPs, LCA can assess the trade-off of the new integration of existing technologies in terms of cost and environmental impact [49]. For example, Meneses et al. [12] concluded that the technologies adopted for more stringent effluent standards from WWTPs (i.e., 10–15 mgN/L and 1–2 mgP/L by EU Urban Waste Water Directive) could improve effluent quality but, at the same time, may require additional energy consumption, use chemical reagents, and produce more sludge. Hauck et al. [50] found the trade-off between different environmental impacts by conducting an LCA. They reported a 16% reduction in marine eutrophication, but the climate change impacts increased with 9% from the traditional operation of the Dokhaven Wastewater Treatment Plant in the Netherlands. This increase was due to the increasing use of electricity and shows that the trade-off between effluent quality and other environmental impacts should not be neglected when applying advanced technology. In nutrient recovery, a similar phenomenon was observed. For example, struvite precipitation for phosphorus recovery improved the effluent quality from WWT while recovering nutrient resources. However, the chemical addition for pH control accounted for up to 97% of total struvite cost [51]. Thus, by applying an established methodology, LCA can identify the trade-off of different technologies adopted in WWTPs.

Besides its benefits, LCA still has a series of shortcomings and limitations, especially related to the data quality and methodology choice. Therefore, research is needed to provide recommendations to future LCA practitioners on the suitable data requirement and impact assessment methodology for WWT. To evaluate these limitations, rigorous assessments should be considered especially from various aspects of the LCA to wastewater treatment to identify the most significant environmental issues, including the economic effects.

6. Evaluation of Sustainable Wastewater Treatment by LCA

The world is moving towards sustainable development and a circular economy. In 2015, the United Nations set 17 sustainability-developing goals. This global strategic platform included developing countries, even though developed countries generally have more resources for sustainable development. One of these 17 goals focuses on water and sanitation. The goal includes supporting developing countries in water and sanitation programmes including water efficiency, wastewater treatment, and recycling and reuse technologies. Some developing countries such as China have planned to build concept WWTPs to reconceptualise water, carbon, and energy systems from the systems level, which can help build a ‘circular economy’ that closes resource loops to achieve sustainable development. Thus, further studies on the sustainable application in WWTPs combined with LCA, especially in developing countries, are crucial for continuous guidance towards reaching a circular economy in the wastewater industry. Hence, it was observed that the top journals publishing on LCA studies were from the Journal of Cleaner Production, Water Research, and Science of the Total Environment throughout 2006–2022 (Figure 6) in line with their respective goals surrounding efficient water management and usage.

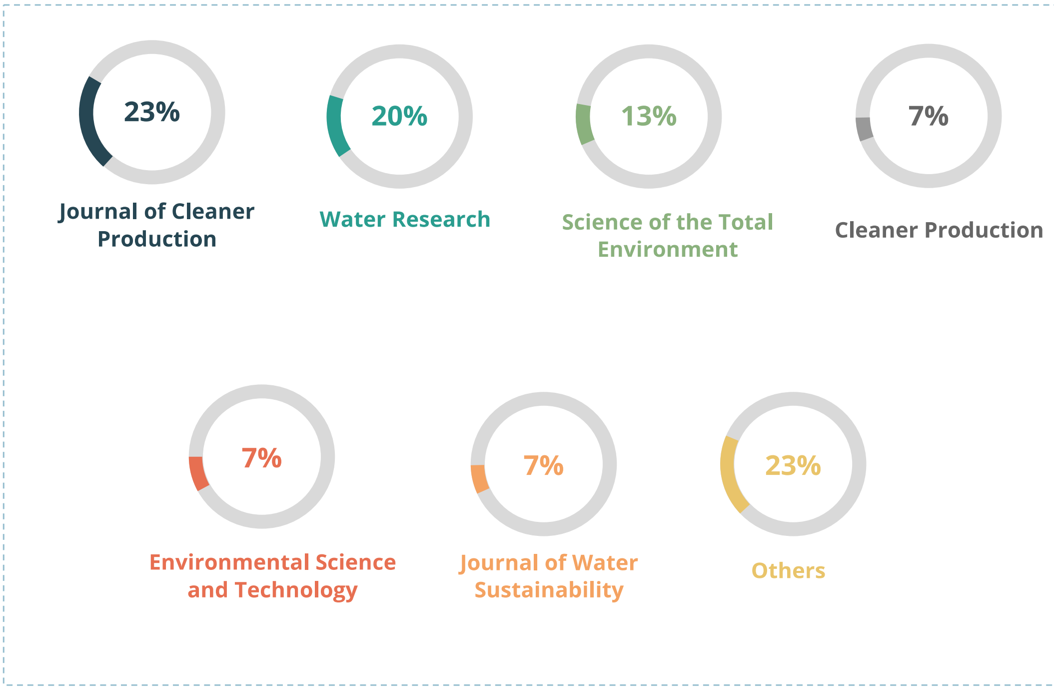

Figure 6. Published LCA studies on WWTP from various journals.

6.1. Sustainable Application in Wastewater Treatment

A WWTP consists of various processes that are typically in series (e.g., pre-treatment, primary treatment, secondary treatment, and sludge treatment) [51]. Each unit has a specific function designed to remove pollutants in wastewater. Pre-treatment largely removes large solids, grit, and oil, whereas primary treatment is designed to remove suspended solids. Secondary treatment is usually based on a biological process that treats organic matter, nitrogen, and phosphorus. Finally, sludge treatment treats the excess sludge by a thickening and dewatering process, and the dewatered sludge is sent to landfills, agriculture land, or incineration plants. An operating WWTP normally uses a large amount of electricity (e.g., for pumping and aeration), as well as chemicals that enhance nutrients removal and improve sludge dewatering process. The operation of a conventional WWTP is not sustainable and generates various environmental impacts such as eutrophication, acidification, and global warming potentials. This chapter reviews and discusses in detail the environmental issues derived from a WWTP and its potential sustainable treatment by using the LCA application.

6.1.1. GHG Emissions

Wastewater treatment operation generates a significant amount of GHGs including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [52,53]. CO_2 is mainly produced from the process of fossil fuels to energy as indirect emissions, which involves with 14–36% of total emissions from a WWTP. Methane is formed in the sewer system and under anaerobic conditions, whereas N_2O contributes to 23–43% of emissions during the biological nitrogen removal process [21,23]. Reducing these direct and indirect emissions from WWTPs could assist in tackling global warming wherein energy reduction and recovery through AD, nitritation–anammox, and A–B process (A stage for carbon capture to improve energy recovery by digestion, and B stage for biological treatment to improve effluent quality) in WWTPs could further reduce GHG emissions. For example, the combination of the anaerobic digestion with combined heat and power, and energy-optimising activated sludge could save over 102,000 tonnes CO_2/year, which equals 50% of energy optimization [54].

However, to quantify the correct emission, an established environmental tool is required because a complex calculation must be completed, including the range of electricity and chemical consumption, as well as site-specific factors. Currently, the quantification of direct GHG emissions is implemented by observing CH_4 and N_2O emission, which present global warming potentials (GWP) of 21 kg CO_2 eq. and 310 kg CO_2 eq. per kg of compound emitted, respectively [55]. The GHGs are produced within the WWTP in various locations and treatments. The main sources of CH_4 emission are in anaerobic conditions such as sludge thickeners and sludge storage tanks [22]. Nonetheless, another important source of CH_4 is the sewer system [56]. Thus, CH_4 is not only emitted from the anaerobic tanks but also in aerated areas via stripping. Meanwhile, N_2O is mainly reported to be released from anoxic zones of activated sludge configurations where nitrification and denitrification reactions lead to the production of N_2O [57]. Additionally, some studies have also pointed out that N_2O emissions occur in de-gritter units, sedimentation tanks, secondary clarifiers, and sludge treatment tanks [58]. Overall, a suitable methodology needs to be identified to calculate GHG emissions from WWTP and find suitable technologies to reduce these emissions.

6.1.2. More Stringent Discharge Standards

The discharging of nitrogenous components of wastewater effluent to a water body can cause the deterioration of water quality and eutrophication to aquatic life [59]. Therefore, the higher limit of effluent discharge from WWT has been introduced especially in urban areas and developed countries such as the USA, Europe, and Japan. For example, the EU Urban Waste Water Directive has set requirements at 10–15 mg N/L and 1–2 mg P/L, which require the improvement and upgrading of wastewater treatment technology such as applying enhanced biological phosphorus removal (EBPR), anaerobic ammonium oxidation (anammox), and aerobic granular sludge (AGS).

Meanwhile, in most developing countries, the discharge requirement is lower because most of the technology is still at a lower efficiency for treatments than that used in developed countries. For example, most of the WWTPs in developing countries only consider nutrient and organic matter removal, whereas most treatment plants in Europe have already applied resource recovery technology such as anaerobic digestion and water reuse technology. Therefore, the scale of environmental impact varies depending on the local factor, as well as regulation and technology adopted mainly for eutrophication impact, which is regularly monitored. The monitoring of effluent data is normally compulsory for all WWTPs to identify the level of nutrients discharged into the water body where it could affect the quality of river or ocean. Thus, the assessment of site-specific discharge standards from a WWTP is crucial, especially in urban areas. These assessments can potentially be used by decision-makers to assess effluent quality regulation and consider upgrading requirements in the future.

6.1.3. Sludge Treatment and Disposal

For the sewage sludge generated from WWT, approximately 10 million and 8 million tonnes of dry sludge were generated in the European Union and United States, respectively, in 2010 [60]. This problem affects the environment where energy is consumed for the treatment and disposal process, polluting underground water and soil by heavy metals and GHG emissions; an estimated 32–39% of CH_4 is emitted from the sludge [53]. Apart from a 90% reduction of sludge volume after incineration [61], integrating technologies of anaerobic digestion and struvite recovery could help to reduce the amount of sludge from WWTPs. For instance, Amersfoort WWTP in the Netherlands, which has commissioned three advanced technologies including struvite recovery by Ostara, could reduce 17% sludge volume while recovering 45% of phosphate and producing 60% more biogas to energy.

6.1.4. Nutrient Removal and Material Recovery

Nutrient removal from WWTPs consists of treatments to remove nitrogen and phosphorus before being discharged to water body and requires different processes. In nitrogen removal, nitrogen is oxidised from ammonia to nitrate through nitrification process, which takes place in aeration tanks/secondary treatment tanks. This process is followed by denitrification where nitrate is converted to nitrogen gas, which is released into the atmosphere and consequently removed from the wastewater. The denitrification process needs anoxic conditions to encourage proper biological reaction. Various technologies are increasingly available for nitrogen removal from wastewater that leads to a cleaner discharge to a water body and sustainable application. For instance, nitrification–denitrification is increasingly applied worldwide due to its technical maturity.

Other nitrogen removal technologies such as aerobic granular sludge (AGS) and anammox are increasingly applied because they have the potential to reduce energy and chemical consumption. Apart from this, the A-stage from the A–B process removes about 55–65% of the organic load, and approximately 80% of nitrogen elimination is achieved in the B-stage [62]. Phosphorus removal can be achieved by chemical phosphorus precipitation such as using iron chloride. Phosphorus can also be biologically removed using polyphosphate-accumulating organisms (PAOs) in EBPR. PAO could accumulate great quantities of phosphorus within their cells, and separate the phosphorus from the treated water. Other phosphorus removal technologies include ion exchange chemical removal and the emerging aerobic granular sludge (AGS) process.

The regular application of nutrient reuse from WWTPs is applying sludge to agricultural lands such as composting due to the nitrogen and phosphorus content in the sludge, both of which can be nutrient sources for plants. However, not all the sludge can be directly applied to agricultural lands due to the pollutant contents such as heavy metals, which can harm the environment. This is the reason why more nutrient recovery research and application is increasingly conducted worldwide for better, more sustainable consumption. Recently, the focus has been on chemical phosphorus product due to its scarcity. For instance, various technologies have been developed to recover phosphorus from WWTPs such as Ostara from Canada and Gifhorn, Airprex, and Unitika from Japan where the struvite can be sold as fertiliser. For example, struvite crystallisation by Airprex was used to retrieve phosphorus following the anaerobic digestion process and EBPR. Struvite was produced by air stripping the reactor, while adding chemical product such as magnesium.

In addition, P recovery process could improve the effluent quality and minimize sludge production while meeting the stringent P discharge limit (<2 mg/L). In terms of efficiency, the recovery of phosphorus from the side stream can achieve up to 50% of P recovery potential, whereas 90% can be recovered from sewage sludge ashes by incineration. However, the combination of EBPR systems for P removal with P recovery technology has received wide interest because EBPR could increase the potential for P recovery by more than 90% [63]. Meanwhile, floatation is another process that recovers heavy metals from wastewater, including copper, zinc, chromium, nickel, lead, and iron, through mechanisms of either precipitate, ion flotation, or sorptive flotation [64].

6.1.5. Energy Recovery to Achieve Energy Neutral or Positive Wastewater Treatment

Basically, energy can be recovered from WWTPs by the process of anaerobic digestion of sludge. However, according to Stillwell et al. [65], this type of technology can only recover approximately 30–40% of the total energy requirements in WWTPs. Therefore, single technology such as the AD of sludge is not enough to achieve energy-neutral or -positive WWTPs, requiring appropriate optimization and technology improvements. For example, technologies such as anammox or the A–B process have to be integrated into the traditional operation of a WWTP to achieve energy-neutral status. As a reference, the Strass WWTP in Austria, which was designed and operated with two-stage activated sludge plant (A–B process) integrated with side-stream anammox and sludge digestion has significantly achieved an 8% energy surplus [66].

This is possible due to achieving an average energy consumption of 0.3–0.5 kWh/m^3 while the source of carbonaceous materials in wastewater reached a recovery of 1.7 kWh/m^3 energy. Therefore, by combining the emerging technologies such as side stream anammox with the adsorption-biological (A–B) stage process followed by anaerobic digestion (AD), energy self-sufficient wastewater treatment could be achieved. An environmental assessment tool such as LCA can be used to evaluate this technology integration and identify the environmental benefits from the energy recovery. However, an intensive assessment methodology should be identified for a convincing result due to the complex technology integration, which requires every detailed aspect of the design and assessment.

6.1.6. Integrated Technology to Upgrade Wastewater Treatment Plant

Conventional WWTPs remove organic matter for the protection of the aquatic environment. However, with an increasing population, municipal WWTPs are faced with the challenge of ensuring sustainable treatment, which includes nutrient removal and resource recovery. Sustainable wastewater treatment greatly relies on treatment technologies. Several new technologies have been developed to treat wastewater more efficiently with low energy and chemical consumption, great potential for resource recovery, higher effluent quality, reduced sludge production, and reduced GHG emission. However, the vast majority of these novel technologies are still in the early stages of research without foreseeable commercialisation. For the pressing task of achieving or moving towards sustainability, plants must rely on existing and mature technologies. In fact, it has been widely accepted that applying the existing technologies and integrating them effectively can achieve more sustainable wastewater treatment instead of waiting for the maturity of novel technologies [60].

Furthermore, it has been found that some technologies can reduce energy consumption and GHG emissions, whereas others achieve resource recovery. Besides the environmental impact, the integration of various technologies also deals with technical and economic impact assessments to identify those technologies that are technically applicable and economical [67]. However, research on the holistic analysis of integrated technologies in the wastewater treatment area is still a fairly new approach. The lack of a comprehensive analysis about the comparison of the environmental impacts and benefits from integration treatment technology to existing plants hinders the practical application of the proposed technologies [68]. In addition, most of this type of research so far has not considered local factors, which may cause great discrepancies.

Thus, there is a possibility to introduce a new configuration of WWT involving nutrient removal and resource recovery (e.g., water, energy, and nutrients) from suitable existing technologies that may retrofit current technology treatment for the future. WWTPs could generate electricity and heat from the methane produced by sewage sludge in anaerobic digestion, in addition to the energy efficiency, nitrogen and phosphorus removal that has been adopted in many WWTPs mainly to reduce eutrophication impact in the water body. The elimination of phosphorus by chemical precipitation could achieve low phosphate concentration in the effluent, making this technology widely used [69].

A few technologies have been developed towards more sustainable treatment, and among the technologies that have been practised on full-scale systems are EBPR and struvite recovery. EBPR is able to decrease the number of chemicals used for the phosphorus removal [69], and P recovery technology produces a high grade of P minerals in the form of magnesium ammonium phosphate (e.g., struvite—$NH_4MgPO_4{\cdot}6H_2O$) for use as fertiliser [70]. EBPR can be a less expensive process to construct and operate; it also generates less sludge and does not use a chemical substance [71]. Solids generated in EBPR can significantly offset the demand for synthetic fertilisers through integration with P struvite recovery technology [48]. However, this nutrient removal and resource recovery treatment has some limitations, such as increases in energy consumption, chemical consumption, and cost [72], so holistic assessments are needed for the sustainable upgrading of wastewater treatment. Sena and Hicks [73] highlighted that environmental impacts associated with

P recovery that involve infrastructure construction, energy, and chemicals required could outweigh the benefits. Furthermore, hotspot analysis to upgrade WWTPs for nutrient removal and resource recovery is important for the identification and selection of efficient technology.

6.2. Application of LCA to Select Sustainable WWTPs

This review clearly shows that different technologies have been developed, integrated, and applied to achieve energy and phosphorus recovery, improve effluent quality, and reduce GHG emissions. In addition, the successful demonstration of STRASS is an aspiring example to show that utilising a combination of existing technologies can lead to energy-neutral wastewater treatment and gain environmental benefits. As seen, the achievements of this plant are a promising demonstration of the sustainable wastewater treatment system. However, the question on how to apply this to a wider context still needs systematic level assessment in environmental and economic aspects, with consideration for local factors. As more technologies are being developed or applied to upgrade existing wastewater treatments for resource (e.g., water, energy, and nutrients) recovery and more stringent discharge standards are being implemented, environmental impact analysis from different aspects is imperative to achieve 'real' sustainable wastewater treatment. This situation shows that the selection of a mature and efficient environmental and economic assessment tool is important to achieve convincing results towards more efficient wastewater treatment with low impact to the environment.

In essence, sustainable wastewater treatment should, over a long-term perspective, be able to treat wastewater while protecting human health and environment with minimal use of scarce resources. In addition, it should also produce beneficial recovery products and be socially, technically, and financially viable. This is because wastewater, which was previously considered as a disposal liability, can now become valuable resources. Water reuse, nutrient removal and recovery, and energy self-sufficiency are among the core parts of wastewater treatment operations working towards sustainability. Apart from this, other environmental factors such as eutrophication, GHG emissions, and pollution from residual sludge have to be considered at the same time to evaluate the sustainability of wastewater treatment. This is because the current global concern is to identify the trade-off between environmental issues such as eutrophication, global warming, toxicity, and electricity used, with more stringent effluent limits and the increased utilisation of some resource recovery technologies such as struvite precipitation of phosphorus.

Due to the significant effect of upgrading technology to the environment and economic, a few studies have evaluated the effect of upgrading plants compared with the existing treatment. Nevertheless, research regarding upgrading wastewater treatment using LCA are various and inconsistent in terms of technology integration and assessment methodology, and most studies have not included an economic assessment. Studies have been conducted to identify the environmental effects of upgraded processes in WWTPs [4,74], but the complexity of these studies vary with different system boundaries and selected technologies and impact categories. The impact of phosphorus recovery from WWT is rarely considered where, for example, comprehensive and quantitative LCA studies involving the impact of phosphorus struvite recovery from WWT technology are still limited [36]. In fact, only a few studies of LCA focused on energy recovery and, for these, important methodological issues in LCA still need to be addressed. Therefore, due to the lack of methodology consistency and transparency in the current practice for LCA–WWT, it is important to emphasize the need for a robust, transparent, and standard method for sustainable technology assessment.

A holistic assessment is especially important for the mature technology that is increasingly applied worldwide, including in developing countries. In a study by [75], LCA was applied to evaluate the impact from WWTPs with upgrading technology of phosphorus removal. They concluded that biological P removal as a best practice should only be added with a chemical process if necessary, based on the life cycle environmental analysis of two P removal scenarios (e.g., biological versus chemical P removal). The results by Hao et al. [4]

who studied LCA of resource recovery technology (e.g., water reuse, electricity, thermal, and P recovery) of WWTP in China found that thermal energy recovery from sludge incineration significantly contributed to 40% of total resource recovery score, followed by 30% electricity recovery, and achieved net-zero impact from total environmental value. Meanwhile, P recovery only achieved 6% from the total resource recovery process. This review indicates the need to combine both nutrient removal and resource recovery using local data to further identify their impact and benefit to the environment while improving LCA methodology itself.

6.3. Life Cycle Economic Assessment of Wastewater Treatment

Economic assessment is one of the most important criteria in identifying the feasibility and efficiency of integrated technology in WWTPs [49,76]. Evaluation of the capital, operations and maintenance costs, and product revenue are important criteria for technology integration. Standard LCA practices encompass only environmental impacts, which excludes economic and social impacts. However, some researchers have increasingly conducted economic analysis for WWTPs, such as a life cycle costing assessment for the selection of wastewater treatment [77], an economic valuation of environmental benefits from the wastewater treatment process [76], and an economic assessment for greywater recycling using whole life cost (WLC) [78] developed a novel method integrating environmental and economic criteria for selecting the best process for WWTPs.

On the other hand, Lin et al. [79] suggested exploring a weighting system to monetize the environmental issues and convert all the economic and environmental criteria into a single sustainability score. Lorenzo-Toja et al. [26] proposed a system value assessment using LCA and LCC for WWTPs based on ecoefficiency concepts. A modelling approach is needed to have a holistic environmental and economic performance of a diverse process [79,80]. Less than 10% of the reviewed studies included an economic efficiency analysis. Furthermore, none of the previous studies assessed the consequence of product value from the wastewater industry involving energy recovery and nutrient recovery to agriculture in specific countries that integrated with the nutrient removal process. This issue carries some questions about how LCA and LCC can support the creation of a circular economy concept in WWT and ensure a positive environmental impact. Additional questions include where should the substituted materials and products be accounted for and who can claim the benefit.

To answer the questions above, a complete economic evaluation for the integration of the technologies proposed should be included and thoroughly evaluated towards a circular economy and sustainable development. This is because some technologies have not been applied in the wastewater treatment industry, and the recovered products such as struvite have yet to be fully accepted by agricultural organisations especially in developing countries. Therefore, an in-depth evaluation needs to be conducted on the economic aspects of the proposed integrated technology identify its compatibility mainly for energy and nutrient recovery. For example, the market value of recovered product such as P fertiliser could influence the economic situation where the price can be different across the world, depending on the demand, regulations, and social acceptance. In addition, economic evaluations of the capital, operation and maintenance, and product revenue are other important criteria for the integration technology besides environmental factors.

In summary of the environmental and economic assessments, an increasing number of wastewater evaluation methods only focus on a limitation aspect of sustainability, while the roles and contributions of the whole system are difficult to understand and thus could exacerbate problems when planning for achieving sustainability. Therefore, although some work on environmental and economic assessments has been done as mentioned previously, a lack of systematic analysis exists for the sustainable development of integrated WWTPs with resource removal and recovery. Furthermore, even though LCA application in wastewater treatment has grown significantly in the last few years, LCA was not originally designed for wastewater treatment analysis, and thus, some issues exist that could be improved including refining the data inventory, impact methodology, and economic indicators for more reliable LCA. This is because to achieve true sustainability, an assessment from an integrated perspective is needed wherein the environmental impacts of WWTPs do not exceed its benefits [36]. Further research should consider wider impact categories through system analysis that considers temporal, spatial, and local specific criteria of WWTPs. This is because it is important to acknowledge the barriers that may vary based on geographical and cultural contexts [81], so a study should focus on a tropical region, such as Malaysia.

7. Review for the Sustainable Strategies in Malaysia

Local factors such as government guidance, policy, wastewater characteristics, pollution of water bodies, climate, main fuel, and local practices for wastewater treatment could affect the selection of technologies towards sustainable development and environmental impact of the integrated wastewater treatment. Therefore, a detailed review of Malaysia information and related characteristic is further discussed in this section.

Malaysia is located in Southeast Asia with a current population of 32.8 million people, producing the total volume of wastewater of 7.53 million m^3/day. As a developing country, the wastewater collection and treatment coverage is very low. Until 2013, only 50% of the wastewaters treated by mechanized plants while others still use untreated individual septic tanks and oxidation ponds [82]. For the mechanical WWT, activated sludge (AS), aerated lagoons, rotating biological contactors (RBC), extended aeration (EA) and trickling filters are the current treatment technologies used. Malaysia's current strategy is to reduce individual untreated wastewater by planning towards a proper centralised treatment system. With more WWTP facilities to be built, it is in a good position to directly adopt well-developed technologies for sustainable wastewater treatment. This is because more than 90% of current wastewater treatment technologies in Malaysia only involve conventional treatment (i.e., without energy recovery). This type of treatment cannot achieve sustainable operation for the rapid growth of municipal WWTPs.

Moreover, many resources are required such as energy and money for transportation, treatment, and final disposal of sludge. As mentioned before, due to the chemical energy contained in wastewater, it is seen as valuable fuel to supplement power generation in Malaysia. However, it has not yet been determined how policy and environmental regulation from the government of developing country can best serve in improving sustainability. Upon the UN Climate Conference in Paris 2015, Malaysia has striven to reduce 45% of its carbon emission intensity by 2030. Previously, it has introduced a feed-in tariff (FiT) in 2004 and subsequently established the Sustainable Energy Development Authority (SEDA) Act in 2011 to fulfil the national aspiration towards achieving energy self-sufficiency and mitigating climate change. As of 2014, only 3.3% of consumed energy is renewable and produced in Malaysia, while 96.7% of its consumed energy is generated from fossil fuels [83].

Based on this situation, Malaysia has adopted a target of 11% installed renewable energy capacity by 2020. Since the water sector consumes 3–5% of total energy consumption of the country, it is an important factor in leading Malaysia to sustainable development, in which we could include renewable energy and nutrient recovery in WWTP. Moreover, with possibly strong municipal wastewater due to the implementation of separate sewer collection system, and a hot climate throughout the year with temperatures ranging from 22 °C to 32 °C, this situation is more favourable to adopt anaerobic digestion, anammox treatment, and the A–B process. This is because more energy could be recovered from stronger municipal wastewater, less or no energy is required by anaerobic digestion and anammox, and treatment efficiency is higher due to higher bacteria activity at a higher temperature.

On the other hand, the previous survey in 2005 by National Hydraulic Research Institute of Malaysia (NAHRIM) identified that 62% of lakes and reservoirs in Malaysia were in serious eutrophic condition. In 2013, out of 473 rivers monitored by Department of Environment Malaysia (DOEM), 72% were polluted and 6% were classified as heavily polluted [84,85]. As such, the Department of Irrigation and Drainage of Malaysia is working towards cleaner water bodies, having introduced the River of Life Project in 2012 which requires cleaner effluent, especially from WWTPs, even though there is no concrete decision yet on the improvement of the wastewater effluent standard. Current effluent discharge limit to the river is 20–50 mgN/L, 20–50 mg BOD_5/L, and 120–200 mg COD/L, but the phosphorus limit is only required when discharging into stagnant water bodies with 5–10 mg P/L.

Meanwhile, due to rapid expansion in crop production in Malaysia (e.g., rubber, oil-palm, cocoa etc.), the importation of phosphate fertilisers is significantly increasing from China and Australia, amounting to GBP 28.8 million in 2005 and GBP 58.8 million in 2011. Based on this situation, P recovery to fertiliser from WWTP is a favoured option which should be considered. Finally, most of the sludge from WWTP in Malaysia is disposed of in landfills, which could impose potential risk and pollution of the underground water and soil. Therefore, these situations would require more research and planning towards sustainable technology which could reduce the volume of sludge and other environmental impacts. However, the existing technologies from developed countries should be carefully evaluated by considering the difference in culture, land, climate, and economy. Currently, there are a lack of policies and regulations in Malaysia regarding resource recovery from water and wastewater sector. Therefore, based on the future results of this research, the suggestions of new regulation and policy can further be explored on a country-wide basis. For instance, economic incentives to enhance technologies and markets for nutrient recovery from WWTP can be proposed and brought about through regulation.

Although Malaysia is not as ambitious as China, how to develop sustainable wastewater treatment in Malaysia for the global strategic platform of sustainable development is still pressing. The research on sustainable wastewater treatment from the system level is still very new, and little work has been done in the Malaysian context with the consideration of local factors, specifically on the overall environmental impact of wastewater treatment. Therefore, a detailed review of Malaysian information and the related local wastewater situation is further discussed in this section.

In Malaysia, the Environmental Quality Act 1974 (Act 127) is the primary federal legislative for water quality. As for sewage, the latest regulations are set in the Environmental Quality (Sewage) regulations 2009, which are applicable to any premises discharging sewage into Malaysian waters except for housing development with less than 150PE. Therefore, those treatment system developed after 2009 have a stricter standard in terms of concentration limit and numbers of parameters regulated [85]. For example, a phosphorus limit was introduced for the first time in 2009 with 5 mg/L for standard A and 10 mg/L for standard B. The other standard parameters included BOD, COD, suspended solid, pH, oil and grease, and NH_3-N. Indah Water Konsortium Sdn Bhd (IWK) is currently the biggest wastewater treatment operator in Malaysia, managing more than 70% of wastewater treatment management. The list of all effluent discharge limits is shown in Table 2.

Table 2. Environmental Quality (Sewage) Regulation 2009 for new sewage treatment system (Malaysia).

Parameter	Unit	Standard A	Standard B
Temperature	°C	40	40
pH value	-	6.0–9.0	5.5–9.0
Biochemical oxygen demand (BOD_5) at 20 °C	mg/L	20	50
Chemical oxygen demand (COD)	mg/L	120	200
Total suspended solids (TSS)	mg/L	50	100
Oil and grease (OandG)	mg/L	5	10
Ammoniacal nitrogen, AMN (river)	mg/L	10	20
Ammoniacal nitrogen, AMN (stagnant water body)	mg/L	5	5
Nitrate-nitrogen (river)	mg/L	20	50
Nitrate-nitrogen (enclosed water body)	mg/L	10	10
Phosphorus (stagnant water body)	mg/L	5	10

For sewage sludge production from WWTPs, Malaysia generates approximately 5 million m^3 per year. However, the amount has been predicted by Indah Water Konsortium to reach 7 million m^3 per year by 2022. Sewage sludge/biosolids is the sludge waste that has been produced after wastewater is treated in a wastewater treatment facility. This sludge is usually in a dilute suspension form, which typically contains 0.25 to 12% of solid matter. Pathogens, heavy metals, and toxic pollutants are present in the untreated wastewater. Sewage sludge also contains high amounts of heavy metals such as lead, cadmium, nickel, chromium, and copper due to its industrial origin [86,87]. This is why most countries strictly regulate the usage of sewage sludge in agriculture or as a soil amendment because of its potential of being harmful to humans, animals, and the environment [87–89]. Sewage sludge is also comprised of organic matter (e.g., COD) and nutrients (e.g., nitrogen and phosphorus) that make it suitable to be used as an organic fertiliser [88,89]. However, sewage application to land for a long period may result to the accumulation of heavy metals in soil. The increased amounts of heavy metals are dangerous because they are usually non-degradable.

The environmental impacts from WWTP such as greenhouse gas emission, toxicity [88,89], and acidification potentials is not properly measured since they are not regulated by the environment agency. To date, these environmental impacts have been ignored in the regulatory framework. Hence, a detailed life cycle inventory and assessment for identifying a correct environmental burden from WWTP is required. For the life cycle development in Malaysia, by the initial review, existing databases providing for local life cycle inventory involving wastewater management are limited. The Malaysian Life Cycle Inventory Database (MY-LCID) was established in 2005 by the Malaysian government under SIRIM Berhad (Scientific and Industrial Research Institute of Malaysia) but it is still at the very beginning stage and seeking to enhance its contents to wider aspects. This research could provide holistic operational databases acquired from variety sources including operational parameters, site sampling database, government websites, technical reports, and local journal articles. The database is up-to-date and reflects the current environmental performance of wastewater treatment. Table 3 shows the overview of existing study of LCA in wastewater management from 2006 to 2022.

The role of environmental impact and cost assessment is important for the sustainable development of WWTP. The technologies that will be adopted towards sustainable WWT could not only be assessed based on the single factor. Thorough environmental impacts must be evaluated to provide guidance for future policy, and for the water industry to find trade-offs for environmental factors and move towards to sustainable development. To enhance the dependability and reproducibility of results, a more consistent implementation of LCA should be proposed, such as allowing deployment on new or current membrane systems [89,90].

8. Summary and Knowledge Gaps

Based on the overall review, LCA has been used as an effective and efficient methodology for the environmental impact of WWTPs. However, LCA applied for WWTPs is still relatively new compared with other manufacturing processes, especially in the developing countries. The question on how WWTPs can implement LCA to achieve reliable results of their environmental impact still needs further research. Additional questions on how to implement LCA in developing countries such as Malaysia to provide guidance to policy makers and WWTPs on operations and upgrading remain and prove to be challenging. This paper identified three main knowledge gaps of LCA for WWTPs and three challenges in the LCA methodology to address for WWTPs in developing countries such as Malaysia: (1) There is a need to critically assess the influence of seasonality (i.e., dry and wet season) on the environmental impact by LCA; (2) there is a need to investigate environmental impacts from WWTPs in developing countries focusing on the site-specific databases; and (3) there is a need to evaluate environmental sustainability of different processes for upgrading wastewater treatment systems.

Therefore, it is important to upgrade existing WWTPs with regards to nutrient removal and resource recovery for more efficient treatment, but identifying the impacts or trade-offs is also important for future reference, an aspect which is rarely discussed. Secondly, there is a lack of comparisons of environmental and economic impacts for the integrated nutrient (i.e., nitrogen and phosphorus) removal and resource recovery. For example, energy and P recovery could further reduce the other environmental impact within the same treatment scheme, but the economic cost is uncertain due to additional chemical and electricity consumption. The real trade-off between these upgrading systems needs to be identified for future implementation strategies towards more efficient and sustainable WWTPs. This is because, to achieve true sustainability, an assessment from an integrated perspective is needed where the environmental impacts of WWTP should not exceed its benefits [36].

Thus, the comprehensive design for upgrading and a method for evaluating both environmental and economic burdens are needed to provide useful information for policy makers and practitioners on the rectification or upgrading of WWTPs. Thirdly, the lack of environmental impact weighting for different phases of operation leads to difficulties in identifying environmental burden hotspots. Most studies remain limited to single-unit operations such as sludge treatment without conducting a comprehensive impact from the whole treatment. Thus, it is crucial to investigate the hotspot impact from upgrading treatment to identify which process has the most burden. Finally, few studies have been conducted in developing countries especially when involving the integration of nutrient removal and resource recovery. Thus, a comprehensive assessment for evaluating both environmental and economic burdens from site-specific data is needed to provide useful information for upgrading wastewater treatments plants in terms of technical, environmental, and economic impacts.

Table 3. Overview of existing study of LCA in wastewater management from 2006 to 2022.

No	Author	Journal	Country/Area	Goal	Functional Unit (FU)	Processes Considered	Sludge Disposal	Data Source/Inventory	LCIA Method and Tool	Impact Category	Scale
1.	[91]	Egyptian Journal of Chemistry	Iraq	Analysis and evaluation of environmental impacts in AL Najaf wastewater treatment plants	1 cubic meter of wastewater for the studied station	Treatment units related to sewage treatment processes, sludge treatment, and other processes such as construction and material transportation	-	Foreground data: WWTP Background data: Ecoinvent	Tool: SimaPro 7 Method: IMPACT2002 +	GWP, Respiratory Organics, non-renewal energy	-
2.	[92]	Journal of Cleaner Production	Sweden	Evaluating the sustainable value of municipal WWTPs	Volume of wastewater treated (m^3) by the WWTP in one year.	Construction and operation	-	Foreground data: WWTP Background data: Ecoinvent ver 3.2	SimaPro (PhD v 9.0)	GWP, EP, AP, ADP, HTP,	50,000 m^3 of influent wastewater per day.
3.	[93]	Environmental Science and Pollution Research	China	Analysing environmental performance with respect to life cycle GHG emissions and eutrophication impact	1 m^3 of treated wastewater	Construction, operation, sludge treatment	-	Foreground data: WWTP Background data: Gabi	Tool: Gabi	GHG, EP	30,000 m^3/day
4.	[94]	International Journal of Environmental Science and Technology	Brazil	Evaluating environmental impacts of WWTP based on an upflow anaerobic sludge blanket followed by a high-rate aerobic pond	1 m^3 of pre-treated wastewater	Operation	Agriculture	Foreground data: WWTP Background data: Ecoinvent	Tool: OpenLCA 1.9 Method: ReCiPe v.1.13 2008	GWP, GTP, CED, TEP	Capacity to attend 10,000 people
5.	[95]	Cleaner Production	Iran	Evaluating the sustainability of two actual wastewater treatment plants using the eco-efficiency index based on energy and life cycle analysis	Total of produced dry sludge or effluent from Al-Teymour and Khin Arab WWTPs with 453,000 and 472,000 Population Equivalent (PE) during one year starting from April 2017	Operation	Agriculture	Foreground data: WWTP	Method: ReCiPe	GWP, HH	453,000 and 472,000 Population Equivalent (PE)
6.	[4]	Water Research	China	To evaluate environmental impacts of a WWTP and compare with resource recovery option	PE /year	Construction, operation, demolition	-	Foreground data: WWTP Background data: Chinese life cycle database	Tool: - Method: CML2001	GWP, EP, AP, ADP, HTP,	200,000 m^3/day
7.	[96]	Journal of Environmental Management	China	To provide assessment of environmental impacts involving 126 PPCPs in advanced wastewater treatment by LCA	1 m^3/day	Construction and operation	-	Foreground data: WWTP Background data: Gabi	Tool: Gabi 6.0 Method: Usetox and Traci	AP, EP, HTP, GWP, OLDP, FEP	-
8.	[97]	Science of the Total Environment	Egypt	To study environmental performance of different scenarios in developing country	1 m^3/day	Construction and operation	-	Foreground data: WWTP Background data: Ecoinvent	Tool: - Method: CML2000	AP, GWP, EP, POP, OLDP, DARP, TEP, FEP	40,000 m^3/day

Table 3. *Cont.*

No	Author	Journal	Country/Area	Goal	Functional Unit (FU)	Processes Considered	Sludge Disposal	Data Source/Inventory	LCIA Method and Tool	Impact Category	Scale
9.	[98]	Journal of Cleaner Production	Denmark and Sweden	To investigate the contribution of direct CH_4 and N_2O to annual carbon footprint of seven WWTPs	1 mg of input, 1 kg carbon, N and P removed	Operation	On-site incineration and application to agricultural land	Foreground data: WWTP Background data: Ecoinvent, EASETECH, ELCD	Tool: EASETECH v2.3.6 Method: IPCC 2006	GWP	-
10.	[70]	Science of the Total Environment	France	To assess impact of recovered phosphorus from WWTP	1 kg of struvite recovered	Construction and operation	Use for fertiliser	Foreground data: WWTP Background data: Ecoinvent v2.2	Tool: Gabi v6 Method: CML-IA	ADFFP, AP, EP, FEP, MEP, TEP, HTP, OLDP, POP	300,000 PE
11.	[67]	Resources, conservation and recycling	Austria	To analyse impact of P recovery form WWTP	PE/year	Operation	-	Foreground data: Literature Background data: Ecoinvent v2.2	-	GWP, AP	-
12.	[99]	Journal of Cleaner Production	China	To investigate how, and to what extent, the LCA results could be influenced by the adoption of various LCA methodologies, via a case study of a representative WWTP in China	10,000 m^3 of waste-water	Operation, sludge treatment	-	Foreground data: WWTP Background data: Ecoinvent V2.1, Chinese life cycle database (CLCD)	Tool: - Method: CML and e-balance (China)	EP, FWEP, HTP, OLDP, GWP, ADP, ACP	-
13.	[100]	Journal of Cleaner Production	Mexico and Canada	To compare the environmental performance of two WWTP technologies across all environmental impact categories in Latin America and the Caribbean	1 m^3/day	Construction and operation	-	Foreground data: WWTP Background data: Ecoinvent, national database and literature	Tool: - Method: Impact 2002 and Recipe	MEP, GWP, FWEP, PM	-
14.	[26]	Science of the Total Environment	Spain	To set new benchmark regarding environmental performance of WWTPs (different climatic regions—Atlantic and Mediterranean) for summer/winter	1 m^3/day	Construction, operation, sludge treatment	-	Foreground data: WWTP Background data: Ecoinvent 2.2 and Spanish electricity production	Tool: Simapro Method: CML 2001, USES-LCA (heavy metals and PPCPs)	EP, GWP, OLDP, HTP, MEP, FWEP	25,000 PE (Atlantic), 70,000 PE (Mediterranean)
15.	[101]	Water Research	Denmark	Evaluation to capture necessary infrastructure additions, operational changes, and reuse option for EBPR2 and side stream microalgae cultivation in photobioreactor	1 m^3/day	Construction, operation, sludge treatment	Incinerator and microalgal fertiliser	Foreground data: Operating reports of an existing process, databases, and model result. Background data: Ecoinvent (Swiss and European market)	Tool: EASETECH Method: ILCD 2011, Usetox (human toxicity)	GWP, ACP, TEP, MEP, POF, Etox, Htc, Htnc, PM, RD	-

Table 3. *Cont.*

No	Author	Journal	Country/Area	Goal	Functional Unit (FU)	Processes Considered	Sludge Disposal	Data Source/Inventory	LCIA Method and Tool	Impact Category	Scale
16.	[102]	Journal of Cleaner Production	Spain	To identify and quantify the main environmental contributors derived from the treatment of urban wastewater and water reclamation opportunities in Tarragona, Spain	1 m^3/day	Operation, sludge treatment	Agriculture	Foreground data: WWTP Background data: Ecoinvent 3.1 and literature	Tool: Monte Carlo simulation Method: CML 2001	TA, CC, FE, ME, POF, MD, FD, OD, TT, WD, CED	132,000 PE
17.	[12]	Journal of Cleaner Production	Spain	To investigate the main environmental contributors derived from the treatment of urban wastewater and water reclamation opportunities in Tarragona, Spain	1 m^3/year	Operation, sludge treatment	Agriculture	Foreground data: Benchmark simulation model 2 Background data: Ecoinvent-sludge transportation and Spanish Energy for electricity production, literature	CML2000	AP, GWP, EP, PHO, DAR, ODP, TAETP	-
18.	[103]	Journal of Cleaner Production	Korea	Evaluating several wastewater treatment plant (WWTP) processes, including an integrated sludge management system and waste sludge disposal methods in a large city based on life cycle analysis (LCA) and economic efficiency analysis (EEA)	1 m^3/day	Operation, sludge treatment	-	Foreground data: Operation of WWTP Background data: LCI database of Korean ministry of environment	Tool: Gabi Method: CML 2001	AP, EP, GWP, HTP	CAS-340,000 m^3/d A2O-680,000 m^3/d MLE-80,000 m^3/d
19.	[104]	Water Research	France	To propose a holistic, life cycle assessment (LCA) of urban wastewater systems (UWS) based on a comprehensive inventory including detailed construction and operation of sewer systems and wastewater treatment plants (WWTPs)	1 day of operation	Construction, operation, sludge treatment	-	Foreground data: operation of WWTP Background data: Ecoinvent	Tool: Simapro Method: Recipe v1.07	TA, CC, FE, ME, POF, MD, FD, OD, TT, WD, CED	5200 PE
20.	[25]	Water Research	Denmark	To investigate how the basis of inventory data affects the outcome of a WWTP LCA by using specific WWTP located in Denmark based on the TRENS system	1 m^3/day	Operation, sludge treatment	-	Foreground data: operation of WWTP Background data: European Pollutant Release EPRTR) and Transfer Registry, Danish emission monitoring, state of the art LCA, Ecoinvent v2.2	Tool: EASETECH Method: ILCD 2011	GWP, AP, EP, PHO, ETP, PM	265,000 PE

Table 3. *Cont.*

No	Author	Journal	Country/Area	Goal	Functional Unit (FU)	Processes Considered	Sludge Disposal	Data Source/Inventory	LCIA Method and Tool	Impact Category	Scale
21.	[105]	Journal of Cleaner Production	Denmark	To compare four types of wastewater treatment plants	1 m^3/day	Operation, sludge treatment	Incinerator, Agriculture	Foreground data: WWTP Background data: Ecoinvent 2.2, ELCD, and Danish Environmental Protection Agency	Tool: Monte-Carlo Method: ILCD 2011, IPCC, Recipe, UseTox, CML2002	AD, AC, EU, GWP, ODP, HT, TE, MET, FET, PO	Between 20,000 PE to 100,000 PE
22.	[106]	Science of the Total Environment	Spain	To compare three side-stream technologies treating anaerobic digestion supernatant at two different levels, as independent levels processes and as part of a modelled WWTP	1 m^3/day	Operation, sludge treatment	Landfill	Foreground data: WWTP Background data: Ecoinvent 2.2, Swiss centre for life cycle inventory 2012	Tool: Biowin Method: CML2002	AD, AC, EU, GWP, ODP, HT, TE, MET, FET, PO	-
23.	[40]	Water and Environment Journal	India	To compare 4 WWT technologies	PE/year	Operation, sludge treatment	Land application, etc.	Foreground data: WWTP Background data: Ecoinvent 2.2 and literature	Tool:- Method:CML2 baseline 2000	AP, GWP, EP, FWAT, HT, MAET, ADP, TE	ASP:200k PE, UASB-FAL:300k PE, CW:30k PE, SBR:100 k PE
24.	[22]	Water Research	Netherlands	To determine the contribution of methane to the greenhouse gas footprint of a wastewater treatment plant and to suggest measures to curb methane emissions	-	Operation, sludge treatment	-	Foreground data: One-year measurement campaign	-	GHG	360,000 PE
25.	[21]	Journal of Water Sustainability	India	To evaluate and quantify the greenhouse gas emissions, mainly methane and nitrous oxide, from the wastewater treatment system	-	Operation, sludge treatment	-	Foreground data: WWTP	Tool: - Method: IPCC 2006	GHG emissions	33 MLD
26.	[23]	Biotechnology and Bioengineering	Spain	To demonstrate the importance of using process-based dynamic models to better evaluate GHG emissions	-	Operation, sludge treatment	-	-	Tool: Benchmark Simulation Model Platform No. 2 (BSM2)	GHG emissions	-
27.	[55]	Journal of Water Sustainability	Korea	Development of a comprehensive impact assessment of gaseous emission from urban wastewater infrastructure and treatment facilities	-	Operation, sludge treatment	-	Foreground data: WWTP	Method: Technical Guidelines (DCCEE, 2010)	GHG emissions	-
28.	[48]	Water Research	Australia	To analyse 10 different wastewater treatment scenarios, covering six process configurations and treatment standards ranging from raw sewage to advanced nutrient removal	-	Construction, operation, sludge treatment	Agriculture	Foreground data: WWTP Background data: Ecoinvent 2.2 and literature	Tool: Biowin simulator	GHG	-

Table 3. *Cont.*

No	Author	Journal	Country/Area	Goal	Functional Unit (FU)	Processes Considered	Sludge Disposal	Data Source/Inventory	LCIA Method and Tool	Impact Category	Scale
29.	[107]	Bioresource Technology	China	Illuminate the environmental benefit of a WWT and reuse project using LCA model	1 m^3/day	Construction, operation, and demolition	-	Foreground data: WWTP Background data: Chinese database for construction material	Tool: - Method: Eco-indicator 99	Energy use	-
30.	[33]	Cleaner Production	Egypt	Develop scenarios to improve the total environmental performance and the sustainability of Alexandria's urban water system	1 m^3	Operation	-	Foreground data: WTP and WWTP Background data: Literature	Tool: Simapro Method: Eco-indicator	Various	Various scale of water and wastewater treatment
31.	[20]	Environmental Science and Technology	Spain	Identify the environmental impact of a WWTP in order to determine the environmental loads associated with the plant's operation and compare the total environmental impact of the various stages in both water and sludge treatment lines	1 m^3/day	Operation, sludge treatment and disposal	Incinerator, Agriculture, landfill, compost plant	Foreground data: WWTP Background data: Ecoinvent 2.2, Spanish energy mix, and the European model for transport and water	Tool: SiSOSTAQUA Method: CML2002	AP, GWP, EP, PHO, DAR, ODP, ETP	144,000 PE
32.	[46]	Cleaner Production	France	Evaluate the environmental performance of a full scale WWTP	1 m^3 of ww /year	Operation, sludge treatment	Agriculture	Foreground data: Operation Background data: Estimation (air emission) for chemical and electricity	Tool: Simapro Method: CML2000, Eco-indicator 99, EDIP96, EPS, Eco-points97	GWP, ARD, AP, EP, TP	140,000 PE
33.	[19]	The International Journal of Life Cycle Assessment	Spain	Environmental evaluation of the most common technical options for urban wastewater	PE	Operation, sludge treatment	-	Foreground data: Operation Background data: Ecoinvent	Tool: Simapro Method: CML2000,	EU, OP, GWP, ACP, AC, PO, AD, TOXILOGICAL (HT, FET, MET, TET)	72,000 to 125,000 PE
34.	[108]	Environmental Science and Technology	Germany	To provide a modular gate-to-gate inventory model for industrial wastewater purification in the chemical and related sectors	1 m^3	Operation	-	Foreground data: Operation Background data: Ecoinvent	-		>500,000 m^3
35.	[109]	Proceedings of LCE	Belgium	To assess the environmental impact of WWTP using LCA methodology	1 m^3	Construction, operation, sludge treatment	-	Foreground data: Operation	Tool:- Method: eco-indicator 99, CML and Impact 2002+	HT, FWT, MET, TE, EU, AC, GW, FF	170,000 PE

Author Contributions: Conceptualization, S.S.R. and S.N.H.; validation, M.M.H. and Y.-Q.L.; writing—original draft preparation, S.S.R.; writing—review and editing, S.N.H.; visualization, K.K.R. and D.A.T.; funding acquisition, S.N.H. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by [FRGS/1/2022/WAB02/UKM/02/1] and [GGPM-2022-072].

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sikosana, M.L.; Sikhwivhilu, K.; Moutloali, R.; Madyira, D.M. Municipal wastewater treatment technologies: A review. *Procedia Manuf.* **2019**, *35*, 1018–1024. [CrossRef]
2. Al-Raad, A.A.; Hanafiah, M.M. Removal of inorganic pollutants using electrocoagulation technology: A review of emerging applications and mechanisms. *J. Environ. Manag.* **2021**, *300*, 113696. [CrossRef] [PubMed]
3. Nizam, N.U.M.; Hanafiah, M.M.; Mahmoudi, E.; Halim, A.A.; Mohammad, A.W. The removal of anionic and cationic dyes from an aqueous solution using biomass-based activated carbon. *Sci. Rep.* **2021**, *11*, 8623. [CrossRef]
4. Hao, X.; Wang, X.; Liu, R.; Li, S.; Van Loosdrecht, M.C.; Jiang, H. Environmental impacts of resource recovery from wastewater treatment plants. *Water Res.* **2019**, *160*, 268–277. [CrossRef] [PubMed]
5. Morera, S.; Corominas, L.; Poch, M.; Aldaya, M.; Comas, J. Water footprint assessment in wastewater treatment plants. *J. Clean. Prod.* **2016**, *112*, 4741–4748. [CrossRef]
6. Piao, W.; Kim, Y.; Kim, H.; Kim, M.; Kim, C. Life cycle assessment and economic efficiency analysis of integrated management of wastewater treatment plants. *J. Clean. Prod.* **2016**, *113*, 325–337. [CrossRef]
7. Englande, A.J., Jr.; Krenkel, P.; Shamas, J. Wastewater Treatment & Water Reclamation. *Ref. Modul. Earth Syst. Environ. Sci.* **2015**. [CrossRef]
8. Harun, S.N.; Hanafiah, M.M.; Noor, N.M. Rice Straw Utilisation for Bioenergy Production: A Brief Overview. *Energies* **2022**, *15*, 5542. [CrossRef]
9. Campos, J.L.; Valenzuela-Heredia, D.; Pedrouso, A.; Del Río, A.V.; Belmonte, M.; Mosquera-Corral, A. Greenhouse Gases Emissions from Wastewater Treatment Plants: Minimization, Treatment, and Prevention. *J. Chem.* **2016**, *2016*, 3796352. [CrossRef]
10. Campos-Guzmán, V.; García-Cáscales, M.S.; Espinosa, N.; Urbina, A. Life Cycle Analysis with Multi-Criteria Decision Making: A review of approaches for the sustainability evaluation of renewable energy technologies. *Renew. Sustain. Energy Rev.* **2019**, *104*, 343–366. [CrossRef]
11. Awasthi, M.K.; Sarsaiya, S.; Wainaina, S.; Rajendran, K.; Awasthi, S.K.; Liu, T.; Duan, Y.; Jain, A.; Sindhu, R.; Binod, P.; et al. Techno-economics and life-cycle assessment of biological and thermochemical treatment of bio-waste. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110837. [CrossRef]
12. Meneses, M.; Concepción, H.; Vrecko, D.; Vilanova, R. Life Cycle Assessment as an environmental evaluation tool for control strategies in wastewater treatment plants. *J. Clean. Prod.* **2015**, *107*, 653–661. [CrossRef]
13. Escobar, N.; Laibach, N. Sustainability check for bio-based technologies: A review of process-based and life cycle approaches. *Renew. Sustain. Energy Rev.* **2020**, *135*, 110213. [CrossRef]
14. Aziz, N.I.H.A.; Hanafiah, M.M. Application of life cycle assessment for desalination: Progress, challenges and future directions. *Environ. Pollut.* **2020**, *268*, 115948. [CrossRef] [PubMed]
15. Rashid, S.S.; Liu, Y.Q.; Mokhtar, H.; Zainudin, M.R.; Muda, M.F. The review of toxicity emission from municipal wastewater treatment by life cycle assessment. *Gading J. Sci. Technol.* **2020**, *5*, 10–18.
16. Dahiya, S.; Katakojwala, R.; Ramakrishna, S.; Venkata Mohan, S. Biobased products and life cycle assess-ment in the context of circular economy and sustainability. *Mat. Circ. Econ.* **2020**, *2*, 7. [CrossRef]
17. Hanafiah, M.M.; Leuven, R.S.E.W.; Sommerwerk, N.; Tockner, K.; Huijbregts, M.A.J. Including the introduction of exotic species in life cycle impact assessment: The case of inland shipping. *Environ. Sci. Technol.* **2013**, *47*, 13934–13940. [CrossRef]
18. Teodosiu, C.; Barjoveanu, G.; Sluser, B.R.; Popa, S.A.E.; Trofin, O. Environmental assessment of municipal wastewater discharges: A comparative study of evaluation methods. *Int. J. Life Cycle Assess.* **2016**, *21*, 395–411. [CrossRef]
19. Hospido, A.; Moreira, M.T.; Fernández-Couto, M.; Feijoo, G. Environmental performance of a municipal wastewater treatment plant. *Int. J. Life Cycle Assess.* **2004**, *9*, 261–271. [CrossRef]
20. Pasqualino, J.; Meneses, M.; Abella, M.; Castells, F. LCA as a Decision Support Tool for the Environmental Improvement of the Operation of a Municipal Wastewater Treatment Plant. *Environ. Sci. Technol.* **2009**, *43*, 3300–3307. [CrossRef]
21. Gupta, D.; Singh, S.K. Greenhouse gas emissions from wastewater treatment plants: A case study of Nnoida. *J. Water Sustain.* **2012**, *2*, 131–139.
22. Daelman, M.R.; Van Voorthuizen, E.M.; Van Dongen, U.G.; Volcke, E.I.; Van Loosdrecht, M.C. Methane emission during municipal wastewater treatment. *Water Res.* **2012**, *46*, 3657–3670. [CrossRef] [PubMed]
23. Corominas, L.; Alsina, X.F.; Snip, L.; Vanrolleghem, P. Comparison of different modeling approaches to better evaluate greenhouse gas emissions from whole wastewater treatment plants. *Biotechnol. Bioeng.* **2012**, *109*, 2854–2863. [CrossRef] [PubMed]
24. Ontiveros, G.A.; Campanella, E.A. Environmental performance of biological nutrient removal processes from a life cycle perspective. *Bioresour. Technol.* **2013**, *150*, 506–512. [CrossRef] [PubMed]

25. Yoshida, H.; Clavreul, J.; Scheutz, C.; Christensen, T.H. Influence of data collection schemes on the Life Cycle Assessment of a municipal wastewater treatment plant. *Water Res.* **2014**, *56*, 292–303. [CrossRef]
26. Lorenzo-Toja, Y.; Alfonsín, C.; Amores, M.J.; Aldea, X.; Marin, D.; Moreira, M.T.; Feijoo, G. Beyond the conventional life cycle inventory in wastewater treatment plants. *Sci. Total Environ.* **2016**, *553*, 71–82. [CrossRef]
27. Alfonsín, C.; Hospido, A.; Omil, F.; Moreira, M.; Feijoo, G. PPCPs in wastewater—Update and calculation of characterization factors for their inclusion in LCA studies. *J. Clean. Prod.* **2014**, *83*, 245–255. [CrossRef]
28. Hauschild, M.Z.; Goedkoop, M.; Guinée, J.; Heijungs, R.; Huijbregts, M.; Jolliet, O.; Margni, M.; De Schryver, A.; Humbert, S.; Laurent, A.; et al. Identifying best existing practice for characterization modeling in life cycle impact assessment. *Int. J. Life Cycle Assess.* **2012**, *18*, 683–697. [CrossRef]
29. Razman, K.K.; Hanafiah, M.M.; Mohammad, A.W.; Lun, A.W. Life cycle assessment of an integrated membrane treatment system of anaerobic-treated palm oil mill effluent (POME). *Membranes* **2022**, *12*, 246. [CrossRef]
30. Hanafiah, M.M.; Ghazali, N.F.; Harun, S.N.; Abdulaali, H.S.; AbdulHasan, M.J.; Kamarudin, M.K.A. Assessing water scarcity in Malaysia: A case study of rice production. *Desalination Water Treat.* **2019**, *149*, 274–287. [CrossRef]
31. *ISO 14040*; Environmental Management—Life Cycle Assessment—Principles and Framework. International Organisation for Standardisation (ISO): Geneva, Switzerland, 2006.
32. Corominas, L.; Foley, J.; Guest, J.; Hospido, A.; Larsen, H.; Morera, S.; Shaw, A. Life cycle assessment applied to wastewater treatment: State of the art. *Water Res.* **2013**, *47*, 5480–5492. [CrossRef] [PubMed]
33. El-Sayed Mohamed Mahgoub, M.; Van der Steen, N.P.; Abu-Zeid, K.; Vairavamoorthy, K. Towards sustainability in urban water: A life cycle analysis of the urban water system of Alexandria City, Egypt. *J. Clean. Prod.* **2010**, *18*, 1100–1106. [CrossRef]
34. Tomei, M.C.; Bertanza, G.; Canato, M.; Heimersson, S.; Laera, G.; Svanström, M. Techno-economic and environmental assessment of upgrading alternatives for sludge stabilization in municipal wastewater treatment plants. *J. Clean. Prod.* **2016**, *112*, 3106–3115. [CrossRef]
35. Balkema, A.J.; Preisig, H.A.; Otterpohl, R.; Lambert, F.J. Indicators for the sustainability assessment of wastewater treatment systems. *Urban Water* **2002**, *4*, 153–161. [CrossRef]
36. Zang, Y.; Li, Y.; Wang, C.; Zhang, W.; Xiong, W. Towards more accurate life cycle assessment of biological wastewater treatment plants: A review. *J. Clean. Product.* **2015**, *107*, 676–692. [CrossRef]
37. Lorenzo-Toja, Y.; Vázquez-Rowe, I.; Amores, M.J.; Termes-Rifé, M.; Marín-Navarro, D.; Moreira, M.T.; Feijoo, G. Benchmarking wastewater treatment plants under an eco-efficiency perspective. *Sci. Total Environ.* **2016**, *566*, 468–479. [CrossRef]
38. Gallego, A.; Hospido, A.; Moreira, M.T.; Feijoo, G. Environmental performance of wastewater treatment plants for small populations. *Resour. Conserv. Recycl.* **2008**, *52*, 931–940. [CrossRef]
39. Rodriguez-Garcia, G.; Molinos-Senante, M.; Hospido, A.; Hernández-Sancho, F.; Moreira, M.; Feijoo, G. Environmental and economic profile of six typologies of wastewater treatment plants. *Water Res.* **2011**, *45*, 5997–6010. [CrossRef]
40. Kalbar, P.P.; Karmakar, S.; Asolekar, S.R. Assessment of wastewater treatment technologies: Life cycle approach. *Water Environ. J.* **2012**, *27*, 261–268. [CrossRef]
41. Ortiz-Gutiérrez, R.A.; Giarola, S.; Bezzo, F. Optimal design of ethanol supply chains considering carbon trading effects and multiple technologies for side-product exploitation. *Environ. Tech.* **2013**, *34*, 2189–2199. [CrossRef]
42. Muñoz, I.; Gómez, M.; Molina-Díaz, A.; Huijbregts, M.; Fernández-Alba, A.; García-Calvo, E. Ranking potential impacts of priority and emerging pollutants in urban wastewater through life cycle impact assessment. *Chemosphere* **2008**, *74*, 37–44. [CrossRef] [PubMed]
43. Huijbregts, M.A.; Struijs, J.; Goedkoop, M.; Heijungs, R.; Hendriks, A.J.; Van de Meent, D. Human population intake fractions and environmental fate factors of toxic pollutants in life cycle impact assessment. *Chemosphere* **2005**, *61*, 1495–1504. [CrossRef] [PubMed]
44. Rosenbaum, R.K.; Bachmann, T.M.; Gold, L.S.; Huijbregts, M.A.; Jolliet, O.; Juraske, R.; Koehler, A.; Larsen, H.F.; MacLeod, M.; Margni, M.; et al. USEtox—The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *Int. J. Life Cycle Assess.* **2008**, *13*, 532–546. [CrossRef]
45. Pizzol, M.; Christensen, P.; Schmidt, J.; Thomsen, M. Impacts of "metals" on human health: A comparison between nine different methodologies for Life Cycle Impact Assessment (LCIA). *J. Clean. Prod.* **2011**, *19*, 646–656. [CrossRef]
46. Renou, S.; Thomas, J.; Aoustin, E.; Pons, M. Influence of impact assessment methods in wastewater treatment LCA. *J. Clean. Prod.* **2008**, *16*, 1098–1105. [CrossRef]
47. Gallego, A.; Rodríguez-Lado, L.; Hospido, A.; Moreira, M.T.; Feijoo, G. Development of regional characterization factors for aquatic eutrophication. *Int. J. Life Cycle Assess.* **2009**, *15*, 32–43. [CrossRef]
48. Foley, J.; De Haas, D.; Hartley, K.; Lant, P. Comprehensive life cycle inventories of alternative wastewater treatment systems. *Water Res.* **2010**, *44*, 1654–1666. [CrossRef]
49. Mayer, B.K.; Baker, L.A.; Boyer, T.H.; Drechsel, P.; Gifford, M.; Hanjra, M.A.; Parameswaran, P.; Stoltzfus, J.; Westerhoff, P.; Rittmann, B.E. Total Value of Phosphorus Recovery. *Environ. Sci. Technol.* **2016**, *50*, 6606–6620. [CrossRef]
50. Hauck, M.; Maalcke-Luesken, F.A.; Jetten, M.S.; Huijbregts, M.A. Removing nitrogen from wastewater with side stream anammox: What are the trade-offs between environmental impacts? *Resour. Conserv. Recycl.* **2016**, *107*, 212–219. [CrossRef]
51. Doyle, J.D.; Parsons, S.A. Struvite formation, control and recovery. *Water Res.* **2002**, *36*, 3925–3940. [CrossRef]
52. Metcalf and Eddy. *Wastewater Engineering: Treatment and Reuse*, 4th ed.; McGraw-Hill: New York, NY, USA, 2014.

53. Chai, C.; Zhang, D.; Yu, Y.; Feng, Y.; Wong, M.S. Carbon Footprint Analyses of Mainstream Wastewater Treatment Technologies under Different Sludge Treatment Scenarios in China. *Water* **2015**, *7*, 918–938. [CrossRef]
54. Georges, K.; Thornton, A.; Sadler, R. *Evidence: Transforming Wastewater Treatment to Reduce Carbon Emissions*; European Environment Agency: Bristol, UK, 2009. Available online: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/291633/scho1209brnz-e-e.pdf (accessed on 8 November 2022).
55. Listowski, A.; Ngo, H.H.; Guo, W.S.; Vigneswaran, S.; Shin, H.S.; Moon, H. Greenhouse gas (GHG) emissions from urban wastewater system: Future assessment framework and methodology. *J. Water Sustain.* **2011**, *1*, 113–125.
56. Masuda, S.; Suzuki, S.; Sano, I.; Li, Y.-Y.; Nishimura, O. The seasonal variation of emission of greenhouse gases from a full-scale sewage treatment plant. *Chemosphere* **2015**, *140*, 167–173. [CrossRef]
57. Kampschreur, M.J.; Temmink, H.; Kleerebezem, R.; Jetten, M.S.; Van Loosdrecht, M.C. Nitrous oxide emission during wastewater treatment. *Water Res.* **2009**, *43*, 4093–4103. [CrossRef] [PubMed]
58. Harriss, R.; Systems, C.; Hall, M. Nitrous Oxide Emissions from Municipal Wastewater Treatment. *Environ. Sci. Technol.* **1995**, *29*, 2352–2356.
59. Sun, S.-P.; Pellicer-Nàcher, C.; Merkey, B.; Zhou, Q.; Xia, S.-Q.; Yang, D.-H.; Sun, J.-H.; Smets, B.F. Effective Biological Nitrogen Removal Treatment Processes for Domestic Wastewaters with Low C/N Ratios: A Review. *Environ. Eng. Sci.* **2010**, *27*, 111–126. [CrossRef]
60. Wan, J.; Gu, J.; Zhao, Q.; Liu, Y. COD capture: A feasible option towards energy self-sufficient domestic wastewater treatment. *Sci. Rep.* **2016**, *6*, 25054. [CrossRef] [PubMed]
61. Kasina, M.; Wendorff-Belon, M.; Kowalski, P.R.; Michalik, M. Characterization of incineration residues from wastewater treatment plant in Polish city: A future waste based source of valuable elements? *J. Mater. Cycles Waste Manag.* **2019**, *21*, 885–896. [CrossRef]
62. Nowak, O.; Keil, S.; Fimml, C. Examples of energy self-sufficient municipal nutrient removal plants. *Water Sci. Technol.* **2011**, *64*, 1–6. [CrossRef]
63. Urdalen, I. *Phosphorus Recovery from Municipal Wastewater—Literature Review*; Norwegian University of Science and Technology: Trondheim, Norway, 2013.
64. Kyzas, G.Z.; Matis, K.A. Flotation in Water and Wastewater Treatment. *Processes* **2018**, *6*, 116. [CrossRef]
65. Stillwell, A.S.; Hoppock, D.C.; Webber, M.E. Energy Recovery from Wastewater Treatment Plants in the United States: A Case Study of the Energy-Water Nexus. *Sustainability* **2010**, *2*, 945–962. [CrossRef]
66. Jonasson, M. Energy Benchmark for Wastewater Treatment Processes—A Comparison between Sweden and Austria. Benchmarking. 2007. Available online: https://www.iea.lth.se/publications/ms-theses/full%20document/5247_full_document.pdf (accessed on 8 November 2022).
67. Amann, A.; Zoboli, O.; Krampe, J.; Rechberger, H.; Zessner, M.; Egle, L. Environmental impacts of phosphorus recovery from municipal wastewater. *Resour. Conserv. Recycl.* **2018**, *130*, 127–139. [CrossRef]
68. Mininni, G.; Laera, G.; Bertanza, G.; Canato, M.; Sbrilli, A. Mass and energy balances of sludge processing in reference and upgraded wastewater treatment plants. *Environ. Sci. Pollut. Res.* **2015**, *22*, 7203–7215. [CrossRef] [PubMed]
69. Maurer, M.; Boller, M. Modelling of phosphorus precipitation in wastewater treatment plants with enhanced biological phosphorus removal. *Water Sci. Technol.* **1999**, *39*, 147–163. [CrossRef]
70. Pradel, M.; Aissani, L. Environmental impacts of phosphorus recovery from a "product" Life Cycle Assessment perspective: Allocating burdens of wastewater treatment in the production of sludge-based phosphate fertilizers. *Sci. Total Environ.* **2019**, *656*, 55–69. [CrossRef] [PubMed]
71. Blackall, L.L.; Crocetti, G.; Saunders, A.; Bond, P. A review and update of the microbiology of enhanced biological phosphorus removal in wastewater treatment plants. *Antonie Leeuwenhoek* **2002**, *81*, 681–691. [CrossRef]
72. Bashar, R.; Gungor, K.; Karthikeyan, K.; Barak, P. Cost effectiveness of phosphorus removal processes in municipal wastewater treatment. *Chemosphere* **2018**, *197*, 280–290. [CrossRef]
73. Sena, M.; Hicks, A. Life cycle assessment review of struvite precipitation in wastewater treatment. *Resour. Conserv. Recycl.* **2018**, *139*, 194–204. [CrossRef]
74. Hospido, A.; Moreira, T.; Martin, M. Environmental Evaluation of Different Treatment Processes for Sludge from Urban Wastewater Treatments: Anaerobic Digestion versus Thermal Processes. *Int. J. Life Cycle Assess.* **2005**, *10*, 336–345. [CrossRef]
75. Coats, E.R.; Watkins, D.L.; Kranenburg, D. A Comparative Environmental Life-Cycle Analysis for Removing Phosphorus from Wastewater: Biological versus Physical/Chemical Processes. *Water Environ. Res.* **2011**, *83*, 750–760. [CrossRef]
76. Hernández-Sancho, F.; Molinos-Senante, M.; Sala-Garrido, R. Economic valuation of environmental benefits from wastewater treatment processes: An empirical approach for Spain. *Sci. Total Environ.* **2010**, *408*, 953–957. [CrossRef] [PubMed]
77. Rawal, N.; Duggal, S.K. Life Cycle Costing Assessment-Based Approach for Selection of Wastewater Treatment Units. *Natl. Acad. Sci. Lett.* **2016**, *39*, 103–107. [CrossRef]
78. Memon, F.A.; Butler, D.; Han, W.; Liu, S.; Makropoulos, C.; Avery, L.M.; Pidou, M. Economic assessment tool for greywater recycling systems. *Proc. Inst. Civ. Eng. Eng. Sustain.* **2005**, *158*, 155–161. [CrossRef]
79. Lin, Y.; Guo, M.; Shah, N.; Stuckey, D.C. Economic and environmental evaluation of nitrogen removal and recovery methods from wastewater. *Bioresour. Technol.* **2016**, *215*, 227–238. [CrossRef] [PubMed]
80. Haruna, S.N.; Hanafiah, M.M. Consumptive use of water by selected cash crops in Malaysia. *Malays. J. Sustain. Agric. (MJSA)* **2017**, *1*, 6–8. [CrossRef]

81. Larsen, T.A.; Alder, A.C.; Eggen, R.I.L.; Maurer, M.; Lienert, J. Source Separation: Will We See a Paradigm Shift in Wastewater Handling? *Environ. Sci. Technol.* **2009**, *43*, 6121–6125. [CrossRef]
82. Din, M. Special Interview with Datuk Ir Abdul Kadir Mohammad Din, CEO of Indah Water Konsortium (IWK) Returning Malaysia's Rivers To Life: Kuala Lumpur. *Malaysia* **2013**, 1–44. Available online: https://www.yumpu.com/en/document/read/39288651/returning-malaysias-rivers-to-l-malaysian-water-association (accessed on 8 November 2022).
83. Dudley, B. *BP Statistical Review of World Energy—Full Report*; British Petroleum: London, UK, 2016; pp. 1–48.
84. Huang, Y.F.; Ang, S.Y.; Lee, K.M.L.A.T.S.; Lee, T.S. Quality of Water Resources in Malaysia. *Res. Pract. Water Qual.* **2015**, *3*, 65–94. [CrossRef]
85. Ariffin, M.; Sulaiman, S.N.M. Regulating Sewage Pollution of Malaysian Rivers and its Challenges. *Procedia Environ. Sci.* **2015**, *30*, 168–173. [CrossRef]
86. Rashid, S.S.; Liu, Y. Assessing environmental impacts of large centralized wastewater treatment plants with combined or separate sewer systems in dry/wet seasons by using LCA. *Environ. Sci. Pollut. Res.* **2020**, *27*, 15674–15690. [CrossRef]
87. Harun, S.N.; Hanafiah, M.M.; Aziz, N.I.H.A. An LCA-Based Environmental Performance of Rice Production for Developing a Sustainable Agri-Food System in Malaysia. *Environ. Manag.* **2020**, *67*, 146–161. [CrossRef]
88. Rashid, S.S.; Liu, Y.Q.; Zhang, C. Upgrading a large and centralised municipal wastewater treatment plant with sequencing batch reactor technology for integrated nutrient removal and phosphorus recovery: Environmental and economic life cycle performance. *Sci. Total Environ.* **2020**, *749*, 141465. [CrossRef] [PubMed]
89. Razman, K.K.; Mohammad, A.W.; Hanafiah, M.M. Life cycle design and efficiency strategy for sustainable membrane technology. In *Proceedings of the IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2021; Volume 880, p. 012053.
90. Ghani, L.A.; Ali, N.; Nazaran, I.S.; Hanafiah, M.M. Environmental Performance of Small-Scale Seawater Reverse Osmosis Plant for Rural Area Water Supply. *Membranes* **2021**, *11*, 40. [CrossRef] [PubMed]
91. Al-Anbari, M.A.; Altaee, S.A.; Kareem, S.L. Using Life Cycle Assessment (LCA) in Appraisal Sustainability Indicators of Najaf Wastewater Treatment Plant. *Egypt. J. Chem.* **2022**, *65*, 9. [CrossRef]
92. Shanmugam, K.; Gadhamshetty, V.; Tysklind, M.; Bhattacharyya, D.; Upadhyayula, V.K. A sustainable performance assessment framework for circular management of municipal wastewater treatment plants. *J. Clean. Prod.* **2022**, *339*, 130657. [CrossRef]
93. Shao, S.; Mu, H.; Keller, A.A.; Yang, Y.; Hou, H.; Yang, F.; Zhang, Y. Environmental tradeoffs in municipal wastewater treatment plant upgrade: A life cycle perspective. *Environ. Sci. Pollut. Res.* **2021**, *28*, 34913–34923. [CrossRef]
94. Rebello, T.A.; Gonçalves, R.F.; Calmon, J.L. Mitigation of environmental impacts in warm-weather wastewater treatment plants using the life cycle assessment tool. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 4763–4778. [CrossRef]
95. Alizadeh, S.; Zafari-Koloukhi, H.; Rostami, F.; Rouhbakhsh, M.; Avami, A. The eco-efficiency assessment of wastewater treatment plants in the city of Mashhad using emergy and life cycle analyses. *J. Clean. Prod.* **2019**, *249*, 119327. [CrossRef]
96. Li, Y.; Zhang, S.; Zhang, W.; Xiong, W.; Ye, Q.; Hou, X.; Wang, C.; Wang, P. Life cycle assessment of advanced wastewater treatment processes: Involving 126 pharmaceuticals and personal care products in life cycle inventory. *J. Environ. Manag.* **2019**, *238*, 442–450. [CrossRef]
97. Awad, H.; Alalm, M.G.; El-Etriby, H.K. Environmental and cost life cycle assessment of different alternatives for improvement of wastewater treatment plants in developing countries. *Sci. Total Environ.* **2019**, *660*, 57–68. [CrossRef]
98. Delre, A.; Hoeve, M.T.; Scheutz, C. Site-specific carbon footprints of Scandinavian wastewater treatment plants, using the life cycle assessment approach. *J. Clean. Prod.* **2018**, *211*, 1001–1014. [CrossRef]
99. Bai, S.; Wang, X.; Huppes, G.; Zhao, X.; Ren, N. Using site-speci fi c life cycle assessment methodology to evaluate Chinese wastewater treatment scenarios: A comparative study of site- generic and site-speci fi c methods. *J. Clean. Prod.* **2017**, *144*, 1–7. [CrossRef]
100. Hernández-Padilla, F.; Margni, M.; Noyola, A.; Guereca-Hernandez, L.; Bulle, C. Assessing wastewater treatment in Latin America and the Caribbean: Enhancing life cycle assessment interpretation by regionalization and impact assessment sensibility. *J. Clean. Prod.* **2016**, *142*, 2140–2153. [CrossRef]
101. Fang, L.L.; Valverde-Pérez, B.; Damgaard, A.; Plósz, B.G.; Rygaard, M. Life cycle assessment as development and decision support tool for wastewater resource recovery technology. *Water Res.* **2016**, *88*, 538–549. [CrossRef] [PubMed]
102. Pintilie, L.; Torres, C.M.; Teodosiu, C.; Castells, F. Urban wastewater reclamation for industrial reuse: An LCA case study. *J. Clean. Prod.* **2016**, *139*, 1–14. [CrossRef]
103. Piao, W.; Kim, Y.-J. Evaluation of monthly environmental loads from municipal wastewater treatment plants operation using life cycle assessment. *Environ. Eng. Res.* **2016**, *21*, 284–290. [CrossRef]
104. Risch, E.; Gasperi, J.; Gromaire, M.-C.; Chebbo, G.; Azimi, S.; Rocher, V.; Roux, P.; Rosenbaum, R.K.; Sinfort, C. Impacts from urban water systems on receiving waters—How to account for severe wet-weather events in LCA? *Water Res.* **2018**, *128*, 412–423. [CrossRef]
105. Niero, M.; Pizzol, M.; Bruun, H.G.; Thomsen, M. Comparative life cycle assessment of wastewater treatment in Denmark including sensitivity and uncertainty analysis. *J. Clean. Prod.* **2014**, *68*, 25–35. [CrossRef]
106. Rodriguez-Garcia, G.; Frison, N.; Vázquez-Padín, J.; Hospido, A.; Garrido, J.; Fatone, F.; Bolzonella, D.; Moreira, M.; Feijoo, G. Life cycle assessment of nutrient removal technologies for the treatment of anaerobic digestion supernatant and its integration in a wastewater treatment plant. *Sci. Total Environ.* **2014**, *490*, 871–879. [CrossRef]

107. Zhang, Q.H.; Wang, X.C.; Xiong, J.Q.; Chen, R.; Cao, B. Application of life cycle assessment for an evaluation of wastewater treatment and reuse project–Case study of Xi'an, China. *Bioresour. Technol.* **2010**, *101*, 1421–1425. [CrossRef]
108. Köhler, A.; Hellweg, S.; Recan, E.; Hungerbühler, K. Input-dependent life-cycle inventory model of industrial wastewater-treatment processes in the chemical sector. *Environ. Sci. Technol.* **2007**, *41*, 5515–5522. [CrossRef] [PubMed]
109. Halleux, H.; Lassaux, S.; Germain, A. Comparison of life cycle assessment methods, application to a wastewater treatment plant. In Proceedings of the 13th CIRP International Conference on Life Cycvle Engineering, Leuven, Belgium, 31 May–2 June 2006.