Sustainability Assessment of Wastewater Systems: An Environmental and Economic Approach

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Abstract

To address current challenges regarding sustainable development of wastewater treatment and provide scientific support in decision procedures towards sustainable solutions, new approaches, frameworks and methodologies about different possible solutions and their potential sustainability implications are needed. One way to facilitate sustainability assessment of wastewater is Life Cycle Assessment (LCA) methodology; however, it fails to map the full scope of wastewater impacts. This paper presents a framework to evaluate the performance of Wastewater Treatment Facilities (WWTF) taking into consideration various factors for insuring environmental sustainability. A total of nine indicators, seven environmental and two economic related to four wastewater treatment facilities, were assessed. Apart from evaluating the sustainability, this study also discussed the link of life cycle approach and social aspects of wastewater. The results show that for the environmental dimension using LCA provides information on different types of environmental activities and different impact categories. LCA can thus be used to quantify and compare the multiple types of impacts caused by one type of use or emission, as well as the various resource uses or emissions that contribute to one type of impacts. For the economic dimension, there is still a need for consistent and robust indicators and methods. The empirical results suggest that the environmental sustainability framework can be used in the first phase of the decision procedure that leads to a strategic choice for sustainable resource recovery from wastewater in developing countries. This motives researchers and decision-makers to consider the whole picture, and not just individual aspects, when considering different futures scenarios.

Keywords

Environmental life Cycle Assessment, Wastewater Treatment, Economic Costs

1. Introduction

Nowadays, a solid comprehensive sustainability assessment approach is essential in the water and wastewater processes. In the last century, sustainability of wastewater has emerged in many different approaches all over the world, and has become a standard practice in developed nations and a key inspiration in developing countries [1]. The term sustainability describes development "that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2] while the term sustainability assessment can be used to refer to "processes that are *ex* post evaluate techniques as well as those that are forward-looking *ex ante* processes that aim to predict the potential effects of an activity prior to its implementation" [3]. The null universal consensus of these terms and a single way for conducting them are still very limited.

Over the last decades many methods and tools for environmental and sustainability performance have emerged. One of them is life cycle thinking, which represents the basic concept of the whole product system life cycle from cradle to grave. Although life cycle thinking is a qualitative approach, it has been represented by Life Cycle Assessment (LCA), built around the principle of comprehensiveness and therefore it aims to address all environmental interventions. The LCA has been recognized as robust and holist framework for assessing environmental dimensions of sustainability. However, LCA focus on environmental aspects misses the social and economic dimension of sustainability. One form of sustainability assessment over the life cycle is life cycle sustainability assessment [4] comparison the three pillars of sustainability, environment, economy and society. However, the maturity of methodologies and tools, under life cycle framework, is different for three sustainability dimensions [5]. Whereas the environmental dimension is well covered by Environmental Life Cycle Assessment [6]; the economic and social pillars still require fundamental scientific progress. This broad view of sustainability assessment brings with it some additional challenges for both researchers and practitioners, not the least of which is how to make sense of the range of applications, processes and practices that now proliferate [3].

Various studies have been done to solve sustainability assessment related to wastewater issues considering different criteria, through the use of multi-criteria decision analysis [7] [8] [9], the implementation of integer programming conducted by choosing sustainable wastewater treatment systems [10] or applied techniques for order preference by similarity to ideal solutions method to rank wastewater technologies [11]. All of these studies considered, environmental and economic aspects of each technology, but they have prioritized the selection based on their cost, nonetheless LCA was not performed.

Regarding to the sustainability performance of wastewater treatment plants, the integrated sustainability assessment method based on life cycle thinking is highly necessary for selecting the best sustainable technology by considering economic, technological, environmental and social aspects. In this situation,

and, according to Pahl-Wostl *et al.* [12], few studies have taken an integrated and holistic approach related to wastewater treatment plants and sustainability with the full incorporation of all the components defined in literature; economic, social and environmental issues through the life cycle approach. These issues must be addressed in indicators that should integrate concerns about the supply, distribution, quality, environmental and social impacts of wastewater, in order to minimize the negative impact on receiving bodies, ecosystems, agricultural production and society.

To enhance sustainability in wastewater management, public policies must be based in holistic information, supporting the social wellbeing of the population, the maintenance of processes and environmental services and the governance principles. This implies the importance of evaluating the policy, social and economic effects in addition to environmental impact studies [13] [14] [15].

Thus far, the focus on LCAs of wastewater treatment systems has not integrated social nor economic aspects in life cycle approach, but rather than on environmental assessment of wastewater treatment plants [16]. Furthermore, most of the studies that evaluate the sustainability of wastewater have a geographical scope outside of the México [17] [18] [19], focus solely on economic indicators [20] [21] or environmental indicators [18] [22]. To the knowledge of the authors, no environmental sustainability evaluation of onsite wastewater treatment systems has been conducted with reference to considered life cycle thinking in Mexico. To reflect all dimensions of sustainability, this paper focuses on the operation of Wastewater Treatment Facilities (WWTF).

The paper presents an eco-efficiency approach by evaluating the environmental and economic aspects of wastewater treatment facilities to select the most appropriate in terms of water sustainability. Moreover, our aim is to help the public sector gain a better understanding of their improvements and vulnerabilities in the sanitation sector. The framework was applied to four WWTFs in two countries: in Los Angeles Metropolitan Area and Phoenix, in the United States; and in Metropolitan Mexico City (MMC), in México. In this case, we evaluated two facilities in the MMC. These areas face similar challenges in terms of population, economic importance and rapid urban development over relatively short periods.

2. Methodological Approach

In the present study, a multi-decision framework was proposed for selecting the most sustainable wastewater treatment facility in three cities under a life cycle approach as shown in Figure 1. This framework comprises three main steps: 1) environmental evaluation, 2) economic assessment and 3) articulation of environmental LCA and social indicators, each dimension evaluated independently. In addition, a summary table and a figure are presented to visualize the full image of sustainability (economic and environmental dimensions).

The evaluation took into consideration 9 indicators, which, seven of them are, environmental indicators (Abiotic Depletion, AD (Fossil Fuels MJ); Acidification,
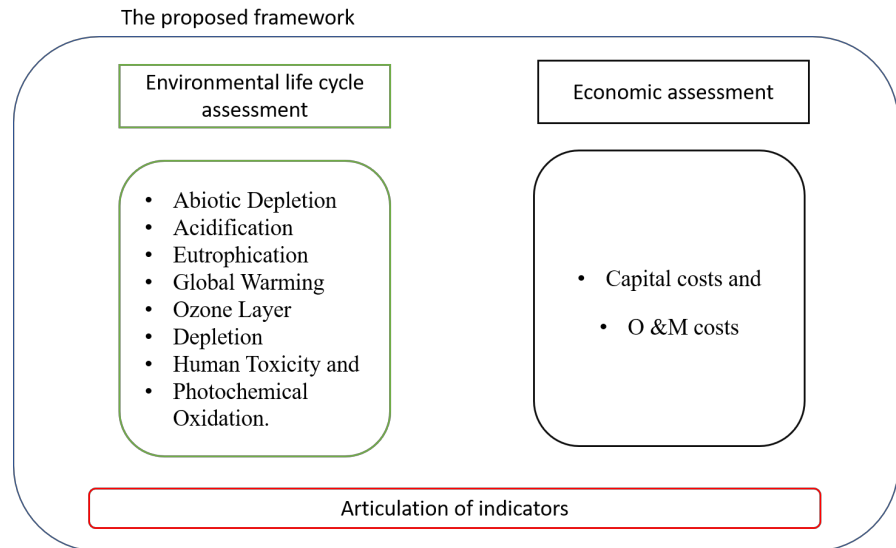
Figure 1. Indicators selected.

AI (g·SO$_2$·eq); Eutrophication, EI (g·PO$_4$·eq); Global Warming, GW (g·CO$_2$·eq); Ozone Layer Depletion, ODI (g·CFC-$_{11}$·eq); Human Toxicity, HTI (g·1,4-DB·eq) and Photochemical Oxidation, POI) and two economic indicators (capital costs and Operation and Management (O & M) costs).

2.1. Environmental LCA

### 2.1.1. Life Cycle Assessment Methodology

LCA is an assessment tool that aims at analyzing the environmental effects associated with a product, process or single activity over the entire course of its life or duration, *i.e.*, from cradle to grave. The International Organization for Standardization (ISO) has published procedures for conducting LCA [6], which provide specific guidelines. LCA consists of four steps: the definition of goal and scope, the development of life cycle inventories, impact assessment, and interpretation. LCA is an iterative process in which the goal and scope are constantly adjusted depending on the data collection limitations and the insights provided by the impact assessment (Bauman and Tillman, 2004). The term "environmental impact" is used in LCA to refer to the effects of the studied system on the environment. These impacts depend directly on the evaluation method used during the impact assessment step. Such assessments are based on the development of a system model that quantifies the inputs (consumption of energy and materials) and outputs (emissions and wastes) released to the environment throughout the entire life cycle of the system. In this study, the ISO 14040 guidelines were applied to assess the environmental effects of wood pellet production from a cradle-to-gate perspective.

2.1.2. Description of the Case Study

The four WWTP analyzed and their characteristics are presented in **Table 1** and the each one of the life cycle systems are presented in **Figure 2**. The functional

Table 1. Descriptions and names of unit process considered in the life cycle impact assessment under study.

WWT	Abbreviation	Location	Technology	Flow range (operation)	Treated water used and sludge disposal
Parque Naucalli	Na	Mexico City	Activated sludge. Aerated extention.	22 L/s	Waterbody discharge, no sludge treatment.
Phoenix	Ph	Arizona	Activated sludge. Completely mixed.	1400 L/s	Waterbody discharge, anaerobic digestion and fertilized.
Los Angeles	La	California	Activated sludge. Completely mixed.	3000 L/s	Waterbody discharge, anaerobic digestion and fertilized.
Iztapalapa	Iz	Mexico City	Activated sludge. Completely mixed.	1500 L/s	Water body discharge and urban reuse, no sludge treatment.
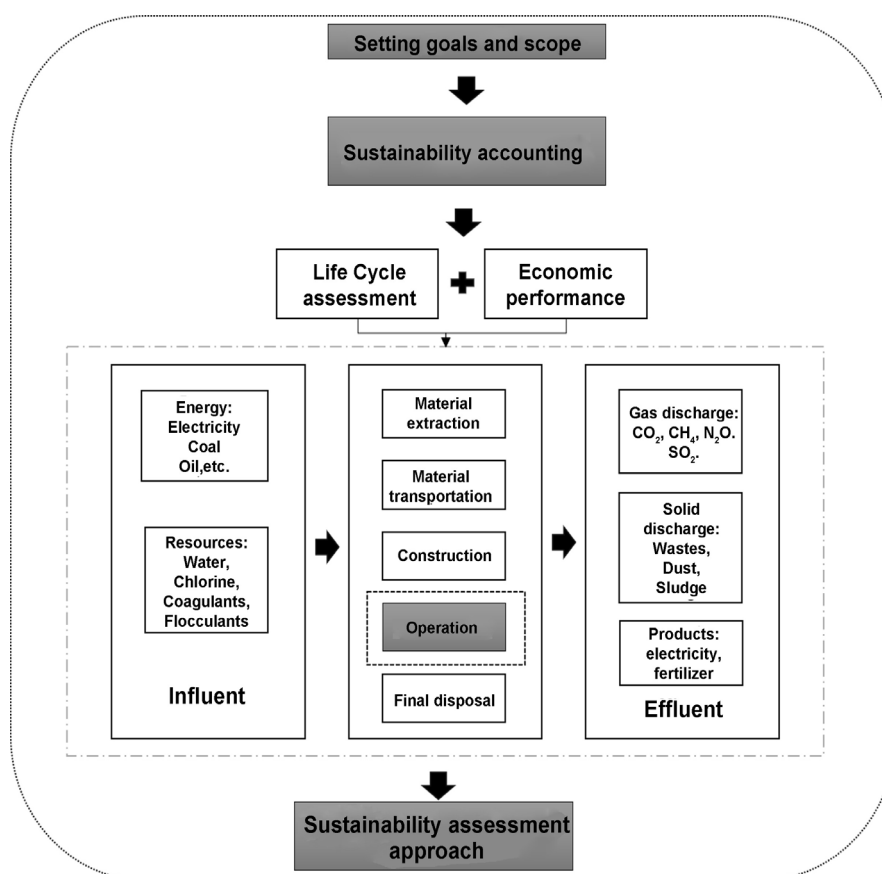
Figure 2. Framework used to evaluate the WWTF.

unit (comparison base), was defined as one cubic meter of treated water (1 m³). The wastewater treatment technologies selected (actitation sludge and derivate) are the most representative (80%) among wastewater technologies according to Noyola *et al.* [23].

2.1.3. System Boundary Description

The system boundaries should include raw material extraction, production of materials and components, operation of the treatment plants as well as disposal and recycling of waste products. However, as Lundie *et al.* [24] and Lassaux *et al.*

[25] have reported, the impact of the operation phase is larger than that of the construction stage. In addition, Tillman *et al.* [26] found that the investment impacts were similar for their different alternatives in contrast to those related to the operation of the treatment systems. Bearing all these in mind, the analysis presented here was limited to the operation stage of the WWTP and no considerations were given to the building and dismantling phases.

Figure 3 presents the system boundary for the gate-to-gate wastewater treatment operations of each facility based on the functional unit described above. The facilities under evaluation were divided into four main systems and one subsystem (sludge management). The wastewater production boundaries cover gate-to-gate emissions, energy, fuels and materials necessary to meet the production system requirements. The systems included in the wastewater treatment facilities were as follows: input of raw water, secondary treatment, tertiary treatment and water disposal.

2.1.4. Life Cycle Inventory Analysis

In the Life Cycle Inventory (LCI), data concerning energy use, resource use, as well as emissions to air and water, were collected for each of the flows that were considered to be relevant. Data was mainly collected from suppliers of treatment facilities, scientific articles, evaluation reports and information from national statistics. The LCI is presented in **Table 2**. We assumed a representative electricity mix for the Mexico sites, according to World Bank [27] and for the states of California and Arizona from Stokes and Horvath [28].

The selection of impact categories are based on two reviews performed by [16] [29] were the most used impact categories analyzed were: Abiotic Depletion, AD (Fossil Fuels MJ); Acidification, AI ($g \cdot SO_2 \cdot eq$); Eutrophication, EI ($g \cdot PO_4 \cdot eq$); Global Warming, GW ($g \cdot CO_2 \cdot eq$); Ozone Layer Depletion, ODI ($g \cdot CFC_{-11} \cdot eq$); Human Toxicity, HTI ($g \cdot 1,4$-DB$\cdot eq$) and Photochemical Oxidation, POI ($g \cdot C_2H_4$).
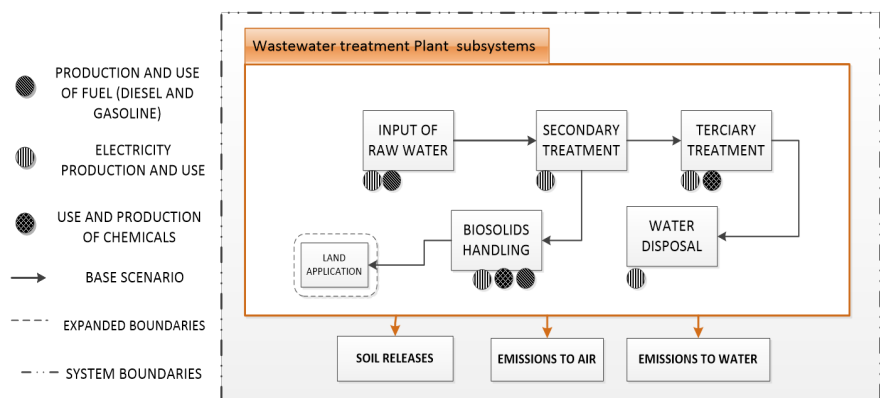

Figure 3. A detailed, schematic diagram of the facilities analyzed. For Na and Iz no Biosolids handling is considered. In activated sludge * correspond to Extended aeration and ** to traditional aeration. In Chlorine * correspond to liquid and ** to gas.

Table 2. Life cycle inventory details.

Parameter (per 1 m³ of treated water)	WWTP1 Na	WWTP2 La	WWTP3 Ph	WWTP4 Iz
Inputs				
Total electricity (kWh)[1]	2.13	0.4454	0.811	0.615
Chlorine (kg)[1]	0.1263	2.15E−02	.0060	0.0869
Polymer (kg)[1]	–––	0.02204	0.3590	–––
Truck use (tkm)	0.00068	0.0245	1.057	0.0035
Outputs				
Energy recovery (kWh)	–––	0.42	–––	–––
Avoided impacts				
P as fertilizer avoided (kg)	–––	0.06459	0.0305	–––
Emissions to water (kg)				
Biochemical oxygen demand	0.048	0.0153	0.002	0.00465
Chemical oxygen demand	0.025	0.02	0.02	0.04034
Total suspend solids	0.014	0.018	0.003	0.00811
Total nitrogen	0.028	0.01	0.00235	0.00546
Total phosphorus	0.0067	0.001	0.0026	0.004955
Mn	0.00019	0.00035	0.00035	0.0000427
Cu	0.000488	0.000043	0.000043	0.00026
Fe	0.00076	0.00013	0.00013	0.0001455
Pb	0.00082	0.00073	0.00073	0.0000689
Zn	0.0000557	0.000081	0.000081	0.0000325
Emissions to soil (kg)				
Sludge (dry matter)	0.068	0.1293	5.28	0.0043
Cd	5.80E−06	0.000085	0.000085	
As	5.12E−06	0.000075	0.000075	3.27E−07
Cu	0.000293	0.00043	0.00043	3.71E−07
Hg	3.89E−06	0.000057	0.000057	2.94E−07
Ni	2.86E−05	0.00042	0.00042	1.83E−06
Pb	5.73E−05	0.00084	0.00084	3.67E−06
Zn	0.0005123	0.0075	0.0075	3.27E−05
Emissions to air				
Biogas produced in anaerobic digestion (m³)	–––	2.054E−06	0.1251	–––

CML IO Baseline V3.01 was the method utilized. The environmental assessment was performed with the support of the software SimaPro 8.02 and Ecoinvent v3 database [30].

2.2. Selection of Study Areas

We selected three large metropolises with wide areas to evaluate four different wastewater treatment facilities. The city selection was based on a comprehensive

qualitative recognition for population, economy, climate and urbanization places identified by [31]. These cities present a connection between vegetation degradation and urbanization among 17 cities of North America and 50 large metropolises around the world and. By this extraction: Los Angeles, Phoenix and Mexico City were chosen for the case study, their selection among the 17 was mainly done by the accessibility to data source, access to installations and research goals by the authors.

2.3. Economic Assessment

The life cycle costing (LCC), the economic branch of life cycle methodology, assesses all costs associated with the life cycle of a product that are directly covered by one or more of the actors in the product life cycle [32].

Considering all costs in the sustainability assessment of the project is undoubtedly the appropriate practice to support the selection of the process, since the actual cost, in this case per cubic meter of treated water (1 m^3), is determined. This involves not only the capital amounts required, but also the costs of operation and maintenance (O&M) over the life of the plant to be built.

The evaluation of this type of indicators helps to characterize the behavior of wastewater treatment facilities (WWTF) in environmental and economic terms [33]; therefore, it helps to prioritize interventions in a context of sustainable decision making.

In this study, we determined the costs from the perspective of the actor, in this case the WWTP. As the systems under study were located in Mexico and USA, the currency selected was the American dollars ($), and the costs assumed were valid for the 2017 year. Both indicators were chosen according to Noyola *et al.* [23].

To evaluate the economic assessment of WWTF only the capital and O&M costs (internal costs) were included within the system boundaries. According, the following economic indicators referring to internal cost were selected:

- The capital cost represents the initial investment of all the facilities for WT processes, [34] pointed out that the capital cost has significant influence on the implementation of the projects about the WT, because the initial investment cost can significantly influence the decision-makers. The capital costs: were divided into the costs for piping, equipment (pump and motor), pump pits, construction expenses, and the contractor's overhead and profits.
- The O&M cost included the costs of electricity, labor, and Maintenance and Repair (M&R). The electricity cost was required for pumping, as well as wastewater treatment, such as the operation of agitators, flocculators and sludge scrapers and maintenance and repairs of machines. The labor cost consisted of operators' wages, as well as their expenses and overheads. The cost in the disposal stage was divided into the costs for recycling, landfill and construction expenses, as well as the contractor's overhead and profits. The M&R cost was assumed to be 3% of a construction cost [35]. The costs were

estimated in detail using databases containing price and cost information (internal reports).

3. Results and Discussions

3.1. Environmental Life Cycle Assessment

The potential environmental impact evaluated for each of the systems analyzed were indexed using the most contributor facility in each impact category as baseline according to data in Figure 3, where can be noted that Naucalpan utility presents higher impacts for AD, AI and HTI, Arizona presents more contributions to GW and POI, Mexico in EU and ODP, while California doesn't present any high impact. The most environmental impacts of the four facilities are generated by the consumption electricity and quality water disposal. Total energy is for the systems (pumping, aeration, etc.)

3.1.1. Acidification

Emissions link to acidification are mainly caused by the production of the electricity used in each WWTP. From smaller to higher impact (kg·SO_2·eq): −0.000579 in Los Angeles, 0.00407 in Iztapalapa, 0.004868 in Phoenix and 0.0109 in Naucalpan. These differences are due to the higher use of electricity in the facility of Naucalpan (2.1 kWh/m^3), five more times than the lowest 0.44 kWh/m^3 in Los Angeles. Nevertheless, these values cannot be compared with those available in literature, likely because of a functional unit factor scale. These results agree with Hospido *et al.* [36] in which they emphasize that the higher amount of water treatment in the facilities has the lower consumption of electricity per functional unit.

3.1.2. Abiotic Depletion (Fossil Fuels)

Depletion of abiotic resources was evaluated using the baseline method described by CML impact assessment method, which is based on ultimate reserves and extraction rates. Results are expressed as fossil fuels consumed given in MJ equivalents per 1 m^3, as shown in Figure 4.

Naucalpan facility generates the highest impact (16.36 MJ), followed by Iztapalapa (5.03 MJ) and Phoenix (7.25 MJ), while Los Angeles produces 0.366 MJ. These values are due to the production of electricity used and the avoided impacts by the manufacture of fertilizers balance effects of the WWTP of this impact category. If this process is disregarded for example in California facility, the comparison is dominated by the avoided burdens associated with the use of sludge as fertilizer in the Biosolids handling system. In the case of case of Naucalpan, Phoenix and Iztapalapa the results show that depletion of fossil resources dominates this impact category in the rest of the facilities.

3.1.3. Global Warming

The results from global warming, with a time horizon of 100 years, agree with the patterns observed in the other impact categories. The global warming impact
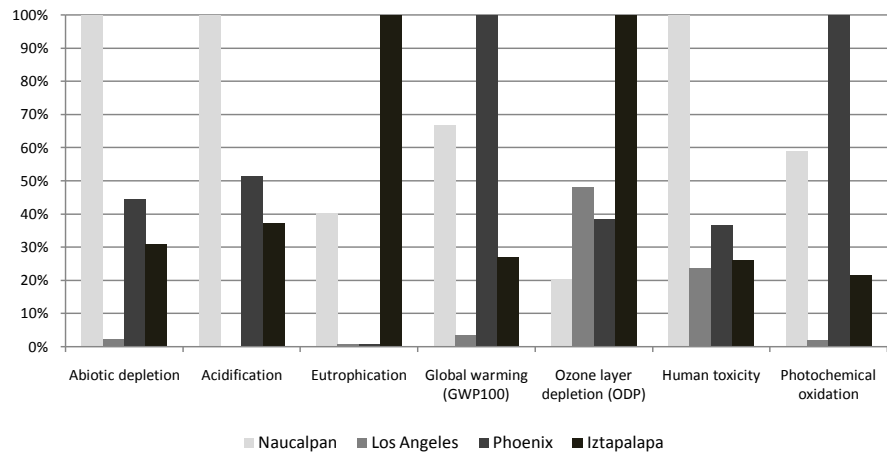
Figure 4. Characterized environmental impacts of the four systems analyzed.

is higher for Phoenix (2.21 kg·CO$_2$·eq), followed by Naucalpan (1.47 kg·CO$_2$·eq), then Iztapalapa (0.60 kg·CO$_2$·eq and the lower impacts are showed by Los Angeles (0.073 kg·CO$_2$·eq). Although this impact can be associated to the high use of electricity, in this case the high impact for GW is presented in the subsystem of biosolids handling due to biogas produced in the anaerobic digestion with no electricity recovery.

Regarding electricity mix, natural gas is used as the primary source of energy in the facilities, accounting for 55%, 35% and 48% of the mix in WWTP Los Angeles, WWTP Phoenix and WWTP Naucalpan and Iztapalapa respectively. This is a factor that determines the measure of global warming potential, so greenhouse emissions can directly be related to the energy mix used in this assessment.

A detailed analysis was carried to identify the subsystems that contribute most to the global warming impact. In WWTP Naucalpan, the secondary treatment and sludge handling account for more than 50% of the total value of the impact category. The greenhouse gas emissions are directly related to the energy consumption. The activated sludge system, as expected, presented the highest environmental burden in the global warming category, when compared to the other subsystems, due to the high energy input for aeration.

From the Los Angeles case study (0.074 kg·CO$_2$·eq), the secondary treatment (activated sludge and secondary clarifier) and tertiary treatment are the most significant contributors to Greenhouse Gas emissions (GHG) (52%). However, the sludge handling attains the lowest share (−57%) in this impact category for all four wastewater treatment alternatives because in the facility methane is captured from anaerobic digestion and is used to generate electricity onsite, which offsets purchased electricity from alternate sources, thereby reducing operational impacts relative to other subsystems. The case study utility's gas recovery program captures essentially all their methane and prevents these emissions from being a more significant contributor. If methane emissions were not captured, the GHG results for this activity would increase 25 times [28].

Phoenix shows a particular behavior in global warming category, in this case, the sludge handling represents by itself more than 70% of emissions, the rest of the subsystems contribute little to the case study results, like **Figure 5** shows. The amount of greenhouse gases produced from this subsystem is related with the sludge digestion and the production of methane from the anaerobic decomposition of sludge. In addition, the inexistence of an electricity recovery program, and therefore, the gas produced then flared and vented increase exponentially the environmental effects in global warming category.

In the case of Iztapalapa (0.596 kg·CO_2·eq) the activated sludge system presented the highest environmental burden in the global warming category (53%), when compared to the other systems, due to the high energy input for aeration.

3.1.4. Eutrophication

Eutrophication was evaluated using the baseline method described in CML-IA methodology is defined for the midpoint approach [37], which is based on generic eutrophication potential (EP) factors. Results are given in kg PO_4^- equivalent per FU (1 m^3), where WWTP Iztapalapa has an impact of 1.069, the biggest of the facilities compared to the 0.43 in Na and 0.0084 in Phoenix and Los Angeles. The impacts of Naucalpan and Iztapalapa are due to the bad practices in the Biosolids handling, such as the discharges to the water bodies (water disposal subsystem) which totally determine the impact on eutrophication. Despite the fact that the WWTP Naucalpan and Iztapalapa were not designed for phosphorus removal, eutrophication arising from emissions of nitrogen to water was included in the initial assessment. Los Angeles and Phoenix showed the most favorable results for eutrophication potential due to the strict laws for water disposal into water bodies, having a care in the removal of nutrients.

The detailed analysis performance show that two substances were found to account for more than 90% of the total value of the impact category, ammonium and phosphorus, which agrees with Hospido *et al.* [36], where she reported that ammonia and phosphorus are the two main substances that impact eutrophication category.

3.1.5. Ozone Layer Depletion

The ozone layer depletion potential is superior for Iztapalapa (0.0000001581 g·CFC-11·eq) than for Naucalpan (0.0000000322 g·CFC-11·eq), Los Angeles (0.0000001131 g·CFC-11·eq) and Phoenix (0.0000000901 g·CFC-11·eq), due to the consume of electricity for pumping and aeration in the facilities and the diesel used in the transportation of the sludge and wastes for final disposal.

3.1.6. Human Toxicity

The impact category of human toxicity is higher for Naucalpan (0.738774 kg·1,4-DB·eq) than for Los Angeles (0.449079 kg·1,4-DB·eq), Phoenix (0.412274 kg·1,4-DB·eq) and Iztapalapa (0.212998 kg·1,4-DB·eq). This is because the heavy metals in the sludge (Naucalpan and Iztapalapa), this is due low capacity for removing heavy metals in addition with the high concentration of the samples

analyzed during the data collection, the diesel used in the transportation of the sludge in the case of Los Angeles and Phoenix is also a contributor of human toxicity, which agree with Hospido *et al.* [36]. In this sense, the amount of sludge at the WWTPs is dependent on two opposite aspects: the implementation of secondary treatment and anaerobic digestion. If this occurs, a higher production takes place. And if it happens, a great reduction of sludge is achieved. Iztapalapa and Naucalpan combines both aspects in a negative direction (presence of secondary treatment and absence of anaerobic digestion) so a huge amount of sludge is produced (see Table 1) and an extremely high impact is brought about (Figure 4). On the contrary, Los Angeles and Phoenix merges both effects in a positive sense (absence of secondary treatment and presence of anaerobic digestion), which explains the minor value attained for this impact category (Figure 5).

3.1.7. Photochemical Oxidation

The Photochemical oxidation category was chosen according to Lundie *et al.* [24] that listed PO as one of the categories of relevance to the water industry. In addition Rodriguez-Garcia *et al.* [38] present that 12 g of ethane equivalents are emitted per person equivalent when using a conventional system for wastewater treatment. The values presented here are far higher, being the higher Phoenix with 0.000839 g per fu, Naucalpan (0.000284 g) Iztapalapa (0.000117 g) and Los Angeles with 0.000018 g, as a result of a more significant energy use (direct and indirect) and diesel for transportation, elements that dominates the emissions associated with this impact category.

3.2. Economic Assessment

3.2.1. Capital Costs

The costs calculated for the WWTF are shown in Table 3. The results of the costs analysis show that Na facility (22 L/s) is the most economical in terms of capital costs (79,732 USD/m^3), followed by Iz (1500 L/s), while La (3000 L/s) and Ph (1400 L/s) clearly had the greatest costsper cubic meter of treated wastewater 18,368,000 USD/m^3 and 21,648,000 USD/m^3, respectively. These findings would indicate that the capital costs of the WWTF increase as the flow increase for each L/s of capacity of flow, however there is fluctuation among facilities, which is due to materials, equipment, and the civil works at the time of estimating the budget, which ostensibly affects the value calculated in comparison between USA and Mexico facilities. For the USA facilities, the investment costs are assumed indirectly by the inhabitants of the population benefited, through the financing by national government, while in Mexico WWTF the capital costs are not shown as a benefit or investment for inhabitants.

3.2.2. O&M Costs

Due to scale effect of having wastewater treatment capacity of 3000 L/s and 1400 L/s, La and Ph facilities have the lowest total economic cost per cubic meter of treated water. While Iz and Na presented the highest cost per cubic meter of
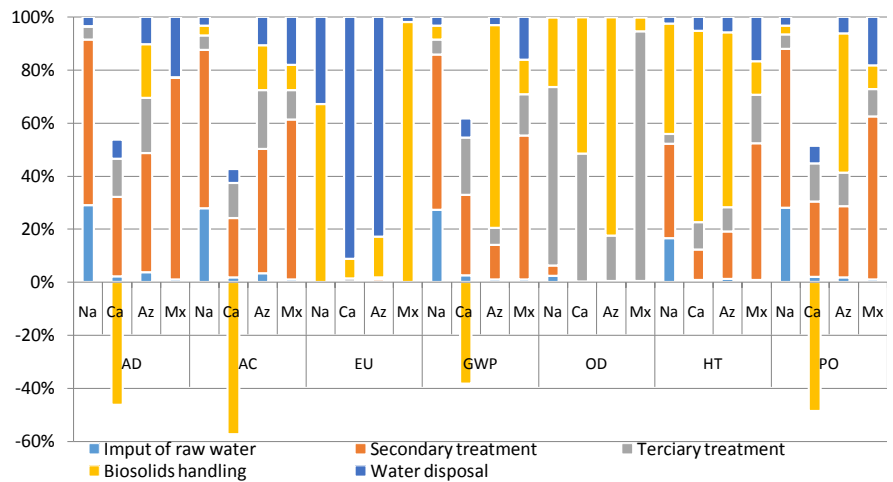
Figure 5. Analysis of contribution per subsystem for the global warming.

Table 3. Capital cost and O&M cost of facilities evaluated.

Indicator	Units	Naucalpan	Los Ángeles	Phoenix	Iztapalapa
Capital costs	USD$/m³	79,732,653.18	18,368,682.29	21,648,804.13	13,745,008.67
O&M costs	USD$/m³	0.60910489	0.055	0.09109	0.109555275

treated water. From and operation and maintenance (O&M) costs, the electricity consumption for pumping and labor costs are the two the principal contributors to the O&M costs.

Since there is no difference of technologies (all four-facilities present activated sludge as main processes) that affect the average consumption energy per cubic meter, the main variation among facilities is the potential to produce electricity by anaerobic digestion of sludge and then use it in the same facilities, this reduce significantly the grid electricity consumption and thus the cost of electricity in the wastewater treatment.

In general, labor cost, due disparity of salaries between Mexico and USA, are much larger in La and Ph facilities, however due the mechanization of technologies fewer personal is required in Ph and La than Na and Iz. Thus, to decrease labor cost by improving management and save energy consumption by upgrading the treatment equipment will be effective alternatives to lower economic cost of wastewater treatment facilities in Mexico.

The economic costs of sludge disposal covered a very little proportion of O&M cost of four wastewater treatment facilities, which means that very little money was used in it. Thus, most of the sludge was disposed of simple landfill, which represents the present situation of sludge disposal in wastewater treatment process in USA.

3.3. Summarized Sustainability Indicators

The evaluation of sustainability under a life cycle approach applied to 4 WWTF considered the application of twelve indicators, seven environmental, three so-

cial and two economic. To present the results of environmental LCA and economic evaluation in a combined and visual tool, a three-degree scale was used, the scale proposed is based on the performance assessment of each indicator, where the best performance is given the "best option", then "intermediate" and the worst performance received the term "worst option". Nevertheless, this scale is just illustrative and does not normalize, judge or weight impact categories, and no discussion about interpretations are presented. Moreover, Figure 6 is only an easy way to visualize the environmental and economic results, and it does not pretend to connect indicators or their influence each other neither to score the results.

As reported in Table 4 and Figure 6, La facility was the best option in ten of twelve categories evaluated, followed by Ph which overall score was intermediate and the worst facility was given to Na for the low performance in six of nine indicators.

For the environmental dimension, La was the best evaluated in five of seven categories evaluated (AD, AI, EI, OD, POI) only GW and HTI presented an "intermediate performance". The performance results for Ph facility were below La, in this case only EI category obtained "best option" qualification, the rest seven indicators were classified as "intermediate option". Iz facility presented the same order of magnitude due to three indicators obtained "intermediate option" (AD, AI and POI) while GW and HTI received the term "best option", only EI and OD were referenced as "worst option". The overall worst performance (worst option) was for Na in three categories (AD, AI and HTI) the rest of indicators were classified as intermediate option.
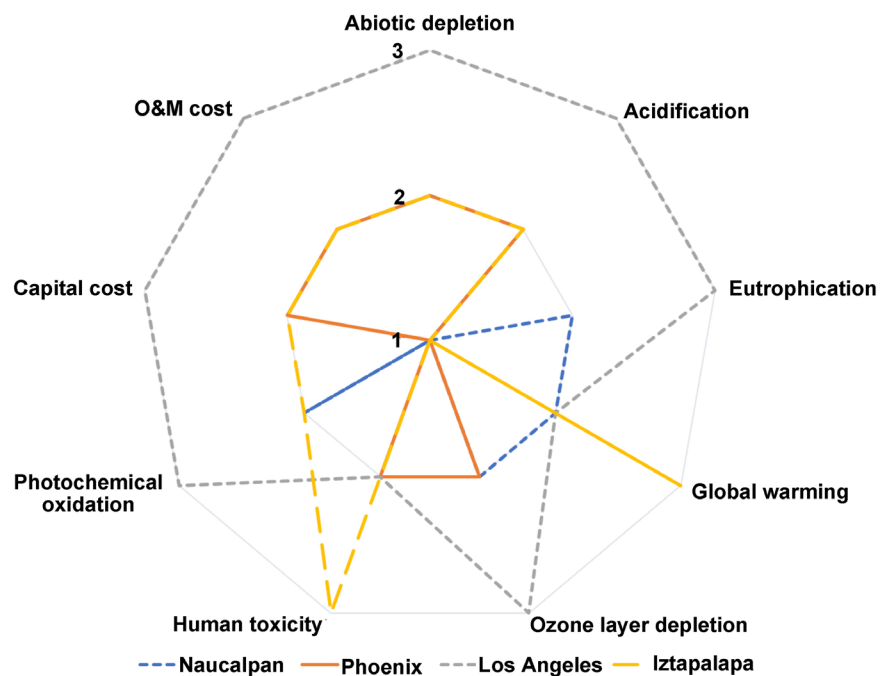

Figure 6. Sustainability scores of the total wastewater treatment facilities evaluated under three-scale performance (1: worst option, 2: intermediate and 3: best option).

Table 4. Life cycle sustainability indicators evaluated in the four WWTF.

Dimension	Indicator	WWTF			
		Na	Ph	La	Iz
Environmental	AD MJ	16.36	7.25	0.366	5.03
	AI (g·SO$_2$·eq)	0.0109	0.004868	−0.000579	0.00407
	EI (g·PO$_4$·eq)	0.43	0.0084	0.0084	1.069
	GW (g·CO$_2$·eq)	1.47	2.21	0.073	0.60
	OD (g·CFC-$_{11}$·eq)	0.0000000322	0.0000000901	0.0000001131	0.0000001581
	HTI (g·1,4-DB·eq)	0.738774	0.412274	0.449079	0.212998
	POI (g·C$_2$H$_4$)	0.000284	0.000839	0.000018	0.000117
Economic	Capital costs (USD$/m^3)	79,732,653.18	21,648,804.13	18,368,682.29	13,745,008.67
	O&M·costs (USD$/m^3)	0.60910489	0.09109	0.055	0.109555275
Table caption		Worst option	Intermediate option	Best option	Intermediate option

Regarding economic evaluation, even though the labor costs and energy price for the operation of facilities in USA were higher than Mexico, the overall costs, related to civil works, waste management, capital cost, etc, were lower (USD/m^3) for Ph and La. It was found that larger the treatment capacity, the lower the O&M costs of wastewater treatment was. The difference of treatment technologies for co-generation affect the unit energy cost of wastewater treatment.

The overall performance obtained, based on both, environmental and economic assessment is as following (from best to worst):

- Los Angeles.
- Arizona.
- Iztapalapa.
- Naucalpan.

4. Conclusions

During this research, a sustainability framework was proposed using life cycle approach for selecting the best sustainable technology by considering economic and environmental aspects. The integration of environmental and economic assessment results in an important feature of sustainability assessment of wastewater since it makes visible the identification of strengths and weaknesses of the facilities.

In the present study, the WWTP Ca attained the most favorable results from an environmental perspective in most of the categories assessed. Within eutrophication impact category, the discharge to the environment of untreated ammonium and phosphorous was identified as the main contributor and, in this sense, we need to consider better actions in the nitrogen and/or phosphate re-

moval in the design of WWTPs.

The WWTP Ca alternative allows the opportunity for heat and energy recovery which can offset fossil fuel consumption and prevent GHG emissions, reducing environmental effects. For the utility, the plant produces approximately 90% of its electricity need using captured methane. If the facility is compared by itself, the GHG emissions are negative, compared to other facilities. It should be noted that the case study utility augments its negative impacts if energy recovery should not be conducted in site. In particular, the aeration subsystem would contribute the increase of global warming factor.

Sludge disposal choices also allow utility to control some of their life-cycle environmental effects. Disposal choices reduce environmental burden because offsets of fuel or electricity consumption or other materials (e.g., fertilizers) can reduce the utility's overall environmental footprint.

Regarding to the facility in Arizona, the electricity consumption, principal contributor to the environmental impacts, could be reduced if an electricity recovery plant, which it means savings of 2000 MWh per annum and carbon footprint reduction of 1400 metric tons, is installed within the current facility. In addition, if biogas is produced, the recovery of the energy content can be possible to minimize all the impacts where the electricity consumption is the contributor of the impacts. So, attention to this should be paid in addition to the energy consumption associated.

The results suggest that the installation of one big WWTP is better, in environmental terms that small WWTP for most of the impact categories analyzed. However, in order to extrapolate the results obtained to other locations, special attention should be taken to wastewater transport, electricity mix and sludge management. The digestion of the sludge also entails several benefits as the sludge is partially stabilized and the volume significantly reduced.

The inclusion of economic aspects, in our study, only the real money flows related to the wastewater were considered, as we could not identify external costs that are likely to be included in the near future. In future works, other perspectives for the Life Cycle Costing analysis of wastewater could be used, for instance, the perspective of the society where the wastewater are applied, and deeper efforts should be devoted assuring the non-existence of external costs likely to be included soon.

Future research is needed to apply and further develop the approach with respect to its conceptual robustness (set of sustainability principles and assessment methodology) and its applicability in participatory and collaborative water modeling and other social indicators. Providing a process for, and results from, sustainability assessments of future scenarios leaves room for transparency, criticism and discussion regarding sustainable development in the process of sustainability water resources.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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