Hindawi
International Journal of Chemical Engineering
Volume 2024, Article ID 5991815, 10 pages
https://doi.org/10.1155/2024/5991815

Research Article

Impact Evaluation of Wastewater Treatment Based on the Anaerobic Digestion of Sewage Sludge Using the Life Cycle Assessment Method

Mohammad Rahmati,[1] Majid Rasouli ,[1] Hossein Haji Agha Alizadeh ,[1] and Behnam Ataeiyan [2]

[1]*Department of Biosystems Engineering, Faculty of Agriculture, Bu-Ali Sina University, Hamedan, Iran*
[2]*Department of Mechanical Engineering of Biosystems, Aburaihan Campus, University of Tehran, Tehran, Iran*

Correspondence should be addressed to Majid Rasouli; m.rasouli@basu.ac.ir

Received 12 January 2024; Revised 17 March 2024; Accepted 27 March 2024; Published 5 April 2024

Academic Editor: Jie Fu

All the inputs and outputs of a technical system can be interpreted from an environmental point of view. Using the life cycle assessment (LCA) approach, some changes that are less harmful to the environment can be included in the system. This research aims to evaluate the environmental effects of the wastewater treatment plant (WWTP) in South Tehran, and the LCA method was used in this study. Based on the data of qualitative parameters obtained from the measurement of Tehran province's water and sewage company, the environmental emissions were calculated and analyzed using SimaPro software (9.0.0) and the standards defined under the ReCiPe 2016-midpoint method. In the ReCiPe 2016 method, the results were expressed in two intermediate levels (including three classes of influence) and final (including 18). The results showed that the treated wastewater and chlorine factors had the most adverse environmental effects. Among the 18 effect classes, the treated wastewater in the class of marine environmental toxicity with the amount of 101.1531 kg 1,4-DCB had the most environmental impacts among other classes. The power consumed by the biogas-burning combined heat and power (CHP) unit in the wastewater treatment (WWT) process reduced the environmental effects in most impact classes. The most adverse environmental effects of the WWT process are related to damage to human health and the ecosystem. According to the findings, the use of CHP systems is suggested for energy saving and also for reducing harmful effects on the environment.

1. Introduction

With the growth in population and urbanization, the absorption capacity of the environment is decreasing daily. WWTPs have been developed to protect the environment from harmful compounds humans produce [1]. With the expansion of industries, the increase in water consumption, and the limitations of water resources, the collection and treatment of urban and industrial wastewater have gained double importance [2]. In such a situation, the use of nonconventional water, including the effluent from the WWTP, in various sectors, especially in the agricultural industry, which accounts for the majority of water consumption, is of particular importance; therefore, the work of the WWTP has a significant effect in reducing environmental pollution and returning water to the natural cycle [3]. WWT, which is used to reduce or eliminate pollution and impurities [4], can have environmental effects, such as the intensification of global warming due to the increase of greenhouse gases and the increase in the nutritional value of water resources due to the discharge of wastewater containing recycled nutrients to water sources. Identifying a product's or process's environmental effects allows decision-makers to identify all environmental impacts to adopt an appropriate policy [5].

In this research, the LCA method, which helps managers make the best decisions, was used. LCA is a successful and growing tool that, despite not having a single and specific method and the need to consider various assumptions and parameters to do it, provides reliable and effective results and the facts of damage caused by human systems, processes, and activities to the environment make it more transparent [2]. The use of LCA in WWTPs began in the 1990s. System inputs are usually energy and raw materials, and outputs include water, solid outputs, and other byproducts. The history of LCA in Iran is concise and is less than a decade. Most of the studies conducted in Iran are mainly on waste management [6].

The authors in [7] conducted an environmental assessment of the Khalkhal WWTP's life cycle (LC). For this purpose, information on the input to the system, the effluent output, and the amount of energy and chemicals consumed were collected. According to the available information, the amount of methane and carbon dioxide produced was calculated and analyzed by using SimaPro software and CML 2001 and Eco-indicator 99 methods. This study showed that both methods have the most significant effect in the class of ozone layer destruction, with 100% participation related to chlorine, and it will have adverse environmental effects [8]. The authors investigated the environmental consequences of WWT using SimaPro software and finally reported the lowest effect of acidification [9] and proposed critical points for developing and managing sludge remediation through LCA measures. Most sewage sludge management strategies depend on the physicochemical characteristics of the sewage sludge, specific ecosystem conditions, related costs, and environmental damages. It is necessary to perform an environmental impact analysis and assess the level of sustainability in different technical strategies to minimize the input of resources and the output of waste. The effluent from the WWTP can be used to irrigate agricultural lands and urban landscapes. Also, nitrogen and phosphorus in the treated sludge can be used as fertilizer. Therefore, evaluating the environmental effects of WWTPs and finding solutions to reuse treated sewage and sludge with minimal damage to the environment and humans are a vital issue. A variety of environmental analysis tools such as material flow analysis, environmental impact assessment, strategic environmental assessment, and LCA have been used by researchers to identify environmental impacts. Assessment methods can provide different emission factors for the same impact group [10].

By referring to the previous studies, we observed that there is a lack of environmental impact assessment of wastewater treatment in Tehran's WWTP. Due to the large volume of produced wastewater in the WWTP in the south of Tehran, it is necessary to pay attention to the environmental effects of this treatment plant. This study was carried out to identify critical environmental points of WWT in the south of Tehran.

2. Materials and Methods

South Tehran' WWTP is designed to treat the sewage of four million people, and the sewage flow rate is 450,000 m^3/d. This 110 ha refinery is located southwest of Ray City, south of Tehran. After treatment, the treatment plant's effluent irrigates 50,000 ha of agricultural land in Varamin plain. The sludge produced in this treatment plant is also used as soil fertilizer and softener for farming lands in the region. The refinery and biogas-burning power plant are shown in Figure 1.

The data used in this research includes information related to the refinery's input, such as ammonia, nitrogen, phosphorus, power consumption, and chlorine, as well as the output of these substances.

2.1. Requirements and Standards of LCA. After collecting the required information, based on the factors affecting each other and specific standards in the SimaPro software, it is possible to identify the pollutants and critical points of the refinery. This software can model the ISO 14040 circulars systematically and transparently [11]. LCA is an analytical tool that shows the overall environmental impacts of a product, process, or human activity from raw material acquisition, production, and use to waste management. This comprehensive perspective makes LCA unique among environmental management tools. As seen in all complex assessment tools, LCA has limitations and strengths. The ISO 14040 defines the LCA method in four stages (Figure 2) as follows:

(i) Determining the aim and scope of the study (including the selection of a functional unit).
(ii) Preparation of a list of energy and resources related to materials and emission of environmental pollutants (LC inventory).
(iii) Assessment of potential environmental impacts associated with identified inputs and outputs (LC impact assessment)
(iv) Interpretation of results to help decision-makers make more informed decisions [13].

2.2. Determining the Aim and Scope. The LCA's first phase includes defining the aim and its scope. This section specifies the boundaries, and the authorities adopt the operational unit and allocation methods [14]. The system boundary in LCA studies defines the input and output paths to the system and specifies the processes that should be included in product production [15]. An accurate definition of system boundaries significantly impacts LCA [16]. In this research, 450,000 m^3/d of WWT was considered as the functional unit which means that all emitted pollutants were calculated and reported based on the inputs used to treat 450,000 m^3/d of wastewater. This system consists of the purification steps of pretreatment (sand screening and grease removal), primary treatment (preaeration and sedimentation) and secondary treatment (biological process and sedimentation) up to the end of the production effluent. The stage of the sludge line, simultaneous system, land sedimentation, and sludge burial was not considered. The scope of the LCA study in the South Tehran' Refinery is shown in Figure 3 and the boundary of the South Tehran' Refinery system is shown in Figure 4.

Figure 1: The South Tehran' sewage treatment plant.

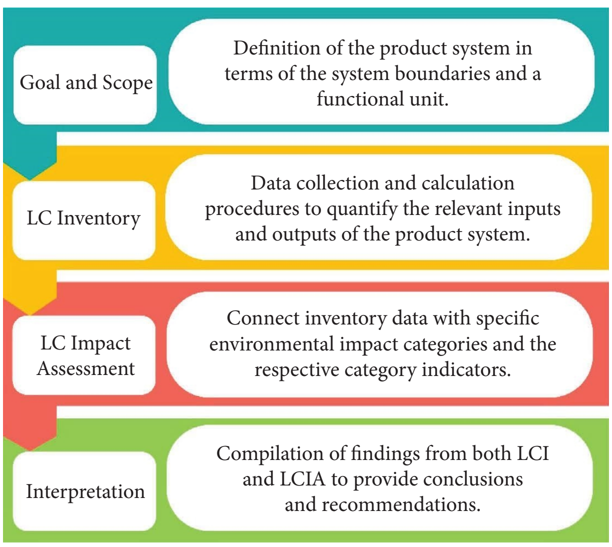

Figure 2: LCA framework [12].

2.3. LC Inventory Analysis. In this step, the resources used and the emission of pollutants in the whole or part of the product LC, which are defined according to the system's boundaries, are considered [17]. This phase includes data collection and calculation stages to determine the quantity of input and output related to a product system [18]. In the inventory stage of the LC of resources, all material and energy flows and the number of emissions of pollutants related to the product's LC are quantitatively defined [19]. LC inventory data directly affect the quality of LCA [14]. In this study, the defined input and output items are listed in Table 1 as an inventory of the LC of WWT. Also, existing data from the case study of South Tehran' WWTP for its LCA are given in Table 2.

The assumptions of the study are as follows:

(i) The impact of construction was not considered.

(ii) Using treated sewage sludge (nitrogen, phosphorus, and ammonia contents) in agricultural soils led to avoiding chemical fertilizers, creating an environmental advantage. Based on the sludge composition, it is assumed that 1 kg of dry sludge is equivalent to 0.3 kg of chemical fertilizer to calculate the amount of avoided fertilizer [20].

(iii) Due to the impossibility of having an accurate data to estimate its effect, this study did not consider the odor issue [21].

(iv) Anaerobic digestion (AD) causes harmful emissions due to the production of sulfur oxide from burning biogas, which is practically negligible due to the low amount of sulfur in biogas composition [21].

(v) Nitrous oxide emission due to incomplete combustion of digester gas is minimal and can be ignored.

(vi) Biogenic carbon dioxide is produced after the ignition of biogas in the flare. The emission of this type of carbon dioxide is not considered in the calculation of greenhouse gas emissions, which can be ignored.

(vii) Methane production rate and methane production potential can be estimated from the number of volatile sludge solids that enter the landfill. For sludge disposal in a landfill, the degradation rate is constant at 0.4 [22].

2.4. LC Impact Assessment. Available data sources can be classified into seven classes: reference, database, statistical yearbook or report (government or business), calculation, simulation, experiment, and interview with experts. Generally, impact assessment and inventory play an essential role in LCA analysis. Limitations in the source, region, and time of existing data affect the quality of the data, while the quality of the data affects the uncertainty of the LCA results. The presented data are crucial for the effectiveness of the LCA in terms of geography and time definition for the entire stages [9]. In this research, using the information of the LC inventory of South Tehran' Refinery, which was collected in the previous stage, an analysis was performed by using the SimaPro software and the standards defined under the ReCiPe 2016 method, and the number of pollutants caused by each of the phases was obtained. These data show a general estimate of pollutant production. The results of the LC inventory analysis are described in the following section.

2.5. Interpretation of Results. The last part of the LC study is interpreting the results, which presents them as a combination of critical sources, consequences, and solutions to reduce them. Interpretation of results helps decision-makers to make more informed decisions. Also, LCA enables the identification of important factors that contribute to the leading environment [13–15, 23]. The collected data in inventory analysis is evaluated in four stages: classification, specification, standardization, and weight analysis [24].

2.6. SimaPro Software. SimaPro software (9.9.0.42) was used to evaluate the environmental effects in this research. This software is a professional tool for assessing the

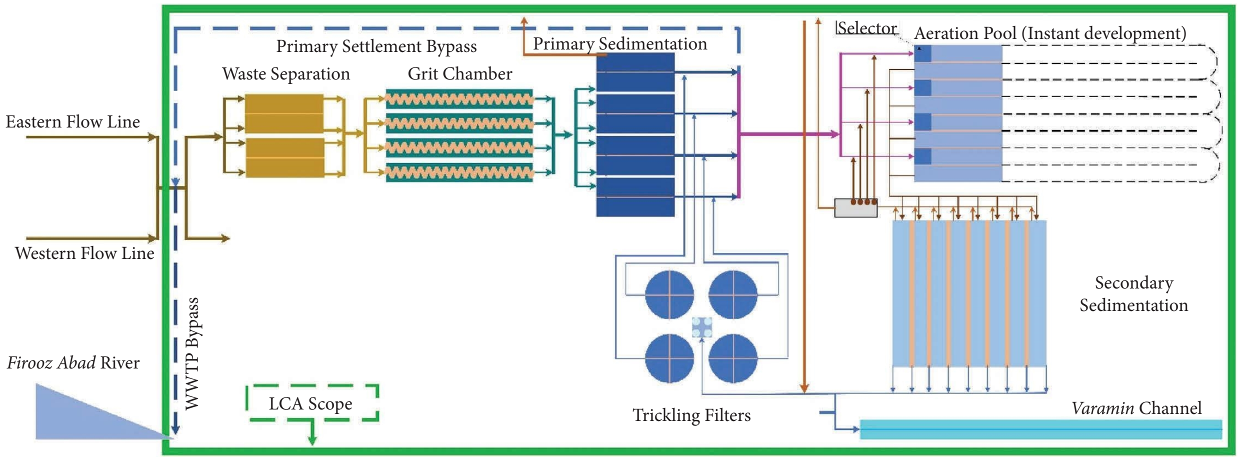

Figure 3: The scope of the LCA study for the South Tehran' sewage treatment plant.

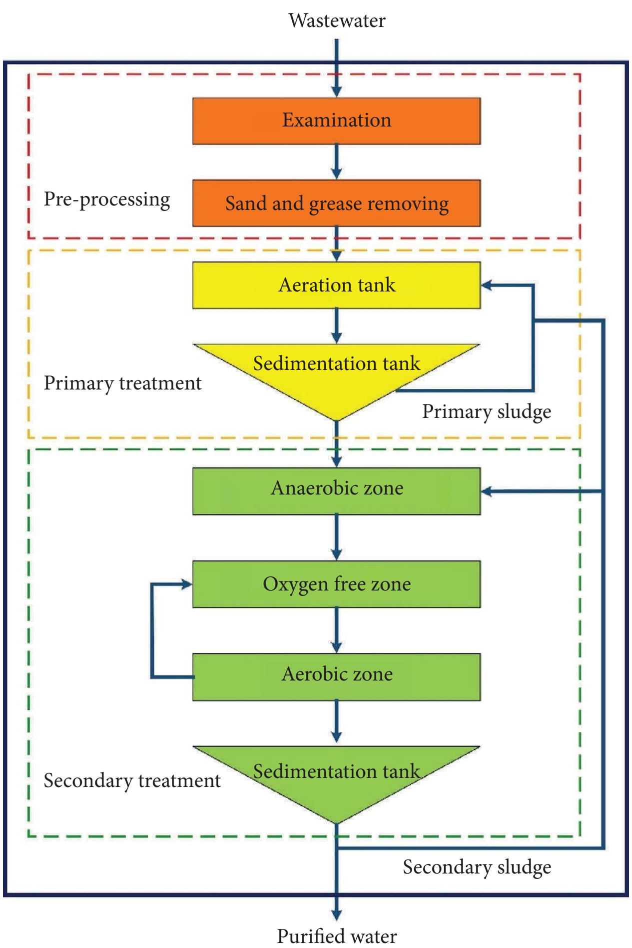

Figure 4: System boundary for the sewage treatment plant.

environmental impact of products, processes, and services. The ecoinvent database is a multipurpose database containing more than 20000 processes [25]. A new assessment method represented by damage classes, subgroups, and streams or substances expresses impacts. This information can calculate LC costs for a product [26]. In SimaPro, there is only one normalization reference and one weighting factor for each group of human health damage, ecosystem quality, and resources, so in this software, resources are normalized, and weighting factors are grouped. Normalization includes the division of the impact assessment results by a specific reference value termed as the normalization reference. This factor significantly influences the results during the aggregation phase [27]. Also, weighting simplifies creating a comprehensive environmental impact measure [28]. Results can be shown as financial values, dimensionless coefficients, or alternative units. The group normalization used in SimaPro differs from the individual normalization sources used in GaBi, which creates a difference between the ratio of specified and normalized results. After the effect weighting step, these differences disappear because the product of group normalization sources and weighting factors used in SimaPro matches the creation of individual normalization sources and weighting factors used in GaBi [29].

Table 1: Inventory data for the whole LCA of the South Tehran' WWTP.

Parameter	Amount per 450000 m^3/d of treated wastewater	Unit
Flow rate	450000	m^3/d
Input BOD	4032.09	mg/l
Output BOD	1097.94	mg/l
Input COD	7572	mg/l
Output COD	2044.44	mg/l
Input SS	4287.18	mg/l
Output SS	492.18	mg/l
Input NH_3-N	359.67	mg/l
Output NH_3-N	151.44	mg/l
Input TN	1609.05	mg/l
Output TN	365.349	mg/l
Input TP	378.6	mg/l
Output TP	208.23	mg/l
Power	174409.662	kv/d
CL	231.8925	kg/h
O_2	110867.331	kg/d
CO_2	296542.236	kg/d
CH_4	550721.025	kg/d

Table 2: Emissions and pollutants of the South Tehran' sewage treatment plant.

Type	Parameter	Amount per 450000 m^3/d of treated wastewater	Unit
Emissions	CO	4050000	g/m^3
	SO_2	13500	g/m^3
	Ozone	36000	g/m^3
	NO_3	22500	g/m^3
	H_2S	360	g/m^3
	NH_3	1260000	g/m^3
	N_2O	814500	g/m^3
	CO_2	36450000	g/m^3
	N_2	18450000	g/m^3
Pollutants	COD	18000	kg/m^3
	SS	4050	kg/m^3
	TN	9000	kg/m^3
	TP	301.5	kg/m^3
	As	4.32	kg/m^3
	Pb	6.75	kg/m^3
	Cd	0.54	kg/m^3
	Cr	1.17	kg/m^3
	Cu	13.5	kg/m^3
	Ni	3.105	kg/m^3
	Zn	14.4	kg/m^3
	Hg	0.009	kg/m^3

The ReCiPe 2016 method was used in this research. This method is distinguished for having two indicator levels: the mid and endpoints. Midpoint indicators analyze impacts along the causal chain with different units for each impact group. These groups include acidification, climate change, depletion of nonliving resources, environmental toxicity, eutrophication potential, human toxicity, ionizing radiation, land use, ozone depletion, suspended particles, and photochemical oxidation. Endpoint indicators analyze the environmental effects at the end of this cause-effect chain and standardize the units of impact classes for three endpoints, including damage to human health, damage to ecosystems, and damage to access of resources [30].

2.7. Characterization or Classification. In this study, the ReCiPe 2016 method was employed. This particular method is comprised of a total of 18 midpoints and 3 endpoints. These specific indicators serve as a comprehensive array of suitable options for effective management strategies or the advancement of future technologies, aiming to prevent potential harm in the field of wastewater treatment. Unlike alternative methodologies, the ReCiPe 2016 method does not factor in the possible consequences of future extractions during the impact assessment process. Instead, it operates under the assumption that these impacts have already been accounted for in the inventory analysis phase [31].

3. Results and Discussion

Inventory information related to the WWTP in the south of Tehran was collected. The analysis of subgroups participating in the sanitary and industrial WWT process with potential environmental effects according to the ReCiPe 2016-midpoint method is discussed as follows.

According to Figure 5, which shows the evaluation of environmental damage for the endpoint indicators, the treated wastewater has many direct emissions in the impact classes, damage to human health and the ecosystem, which is the result of the WWT process, and other items are the result of indirect effects. In the impact class on human health, treated wastewater and power consumed from the power grid have environmental effects, and other cases have a negligible impact. The power consumed from the CHP unit also had reduced effects in this class. In the impact class of damage to ecosystems, treated sewage and power consumed from the power grid had the most environmental effects, and other items had an insignificant impact. In this class, the power consumed from the CHP unit also has reduced impacts. In the class of damage to resources, the power consumed from the CHP unit has the most significant reduction effect, indicating that this item is very effective in reducing the environmental impact. However, the power consumed from the power grid in this class has inappropriate effects on the resources. Generally, consumed power from CHP also has reduction effects in all impact classes, indicating positive environmental impacts.

According to Figure 6, which is the weight chart for endpoint indicators, the impact class of human health damage is more critical and has higher environmental effects than other impact classes because the WWT process is always associated with energy consumption, and it is not possible to save in this field. Therefore, power consumption from the power grid will be one of the influencing factors, and the only way to reduce energy will be to improve the refinery's technology. However, the consumed power from CHP has positive environmental effects due to its self-consumption in the refinery. At the end of the purification process, entering these amounts into the environment will cause environmental impacts. Due to the entry of some pollutants into the ecosystem, treated wastewater has environmental effects.

The results of evaluating the effects of 18 impact classes using SimaPro software in the ReCiPe 2016-midpoint are given in Figure 7. It includes the necessary information such as treated wastewater, used chlorine gas, phosphorous fertilizer in the sludge, nitrogen fertilizer in the sludge, and consumed power in the place, and all the information entered in the software is included according to the effect level in each effect class. The biological resource depletion effect class shows the energy consumption in a system. In other words, it shows the efficiency of a system in helping to reduce fuel consumption. In the acidification effect class, the potential of a pollutant for acidification is measured based on the capacity to produce positive hydrogen ions. In the land use effect class, the effect of nitrogen and phosphorus has been assessed. In the global warming effect class, climate change related to releasing carbon dioxide and greenhouse gases into the air has been investigated. In the class of ozone depletion effect, the measurement criterion is stratospheric ozone per chlorofluorocarbon production. In the class of toxicity effect for humans, the class of risk for humans has been measured in terms of health. In the photochemical oxidation effect class, substances that play a role in forming

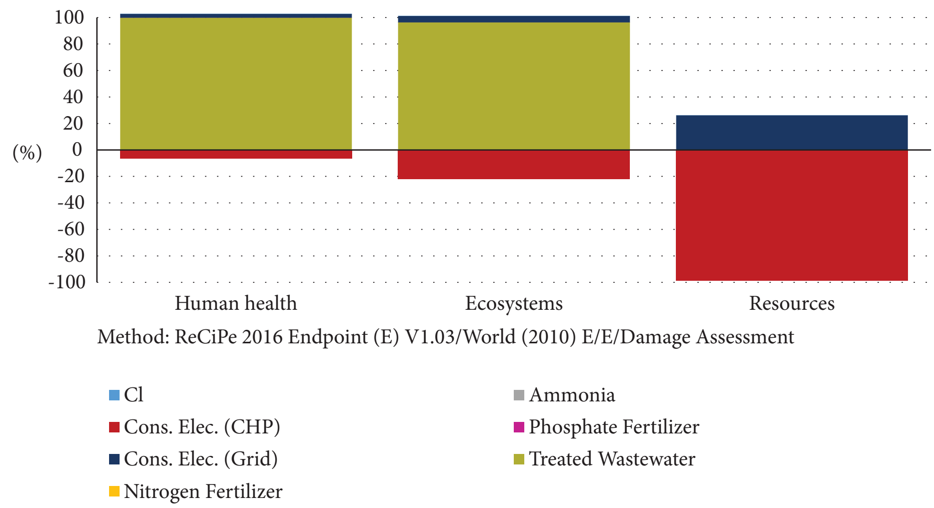

Figure 5: Characteristics of damage in the WWT process.

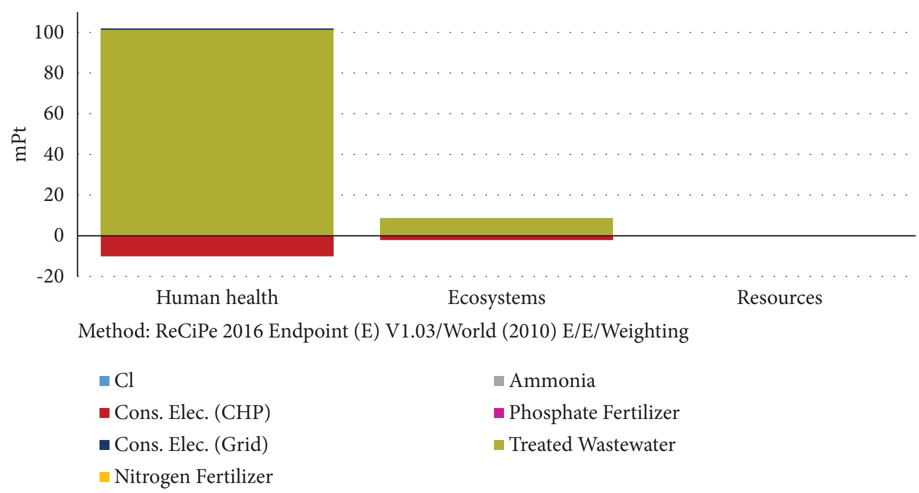

Figure 6: The most significant environmental impacts of the WWT process.

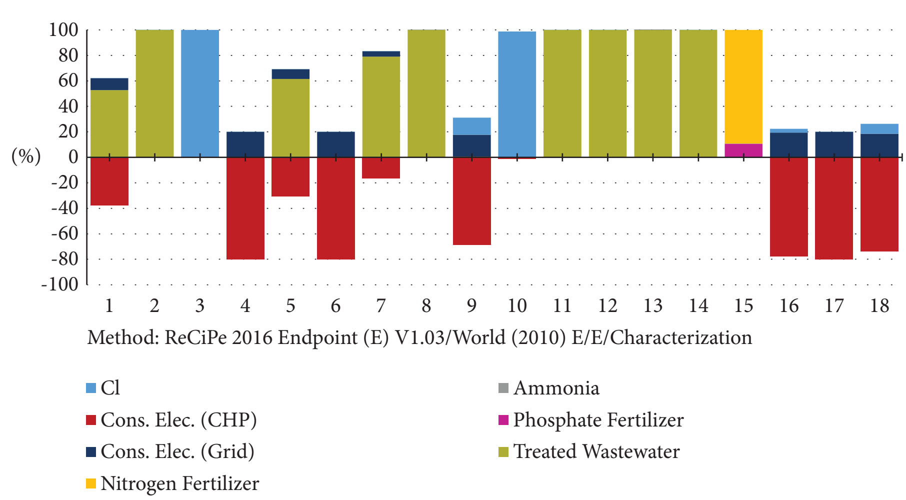

Figure 7: Characterization of the South Tehran' sewage treatment plant system using the ReCiPe 2016-midpoint method.

photochemical ozone in ethylene have been estimated. Other classes also indicate land, drinking, and marine toxicities. The results showed that treated wastewater has the most significant effect in the class of marine environmental toxicity, with a share of 100 %. Also, it has no impact on the impact class of ionizing radiation, ozone formation (human health), ozone formation (terrestrial ecosystems), marine eutrophication, land use, lack of mineral resources, lack of fossil resources, and water consumption. Phosphorus fertilizer, nitrogen fertilizer, and ammonia in sludge are the most toxic in land use. The power consumed from CHP in the eight classes has reduced the environmental effects by a significant amount. However, the power the power grid consumes significantly impacts human health, terrestrial ecosystems, and lack of human resources in the three classes. It has no effect or contribution to the two classes of ionizing radiation and land use.

The findings of this study were consistent with those of other studies. At Buonocore's research, the environmental effects of various scenarios for the disposal of sludge and wastewater at a WWT plant in Southern Italy are compared using LCA. Under scenario B, sludge is anaerobically fermented to produce biogas, which is then used to generate electricity and heat cogeneration. Additional thermal energy from previously recovered waste cooking oil is integrated into the process, and electricity and heat feedback are sent to upstream WWT steps (including sludge drying) before the dried sludge is finally disposed of in a landfill and the water is released into a river. Although it does not significantly enhance FEP, scenario B lowers the process contribution to some environmental effects' categories, such as global warming potential and fossil depletion potential [32]. Also, in a different study, the life cycle environmental effects of four different scenarios for managing sludge were examined. The findings indicate that scenarios for AD showed lower potential impacts than scenarios for lime stabilization in every category that was evaluated, including eutrophication, abiotic depletion, acidification, and climate change in freshwater, marine, and terrestrial ecosystems [33]. The study conducted by Lanko et al. examined the effects on the environment resulting from the AD of sewage sludge in an activated sludge WWTP. The findings show that in the majority of the impact categories examined (i.e., human toxicity, ionizing radiation, metal and fossil depletion, occupation, terrestrial acidification, freshwater eutrophication, and ozone depletion), the WWTP with temperature-phased AD performs better than those with mesophilic and thermophilic AD. The only exception is climate change, where the WWTP with mesophilic AD outperformed those with TPAD by 7%. Except for human toxicity, where credits failed to offset the effects of the wastewater treatment system, the production of heat and electricity (here, considered as avoided environmental impacts) in the sludge line alone resulted in credits in the majority of the impact categories examined [34]. Researchers in a similar study concluded that the main critical point identified in the refinery is related to electrical energy. They also found that sanitary wastewater has worse conditions than industrial wastewater. However, the environmental effects of industrial wastewater should not be ignored, which is consistent with the results of the present study about the resulting wastewater. However, it is against the effect of power. The reason for this difference was the self-consumption of electric energy in the southern Tehran refinery, which has a reduced effect on the environment [35, 36].

According to Table 3, the environmental effects of the first phase are shown in 18 impact classes, according to which, in the global warming class, the highest environmental impact is related to treated wastewater, and the lowest amount is related to phosphorus. In the class of ozone layer destruction, the highest environmental impact is related to treated wastewater, and the lowest amount is related to consumed power from the power grid. In the class of ionizing radiation, the most significant effect is related to chlorine, and the most negligible environmental impact is related to phosphorus, and treated wastewater and consumed power from CHP and the power grid had no effect. In the class of ozone formation, human health and consumed power from CHP have a high contribution to reducing environmental impacts, and the lowest increase in environmental effects is related to phosphorus, and treated wastewater had no effect. In the class of forming fine particles, the consumed power from CHP has reduced environmental impacts, and the lowest impact is related to ammonia. In the class of ozone formation, the earth's ecosystem had the most significant impact related to domestic power consumption, and the most negligible impact was related to phosphorus. Treated wastewater had no effect. In the class of acidification, the highest impact is related to treated wastewater, and the lowest impact is related to ammonia. In the freshwater eutrophication class, the highest impact is related to treated wastewater, and the least unfavorable environmental impact is related to ammonia. In the class of marine eutrophication, the most harmful environmental impact is related to chlorine, and the most negligible impact is related to ammonia. In the terrestrial environmental toxicity class, the most significant effect is related to chlorine, and the most insignificant impact is related to treated wastewater. In the freshwater environmental toxicity class, the highest impact is related to treated wastewater, and the lowest is related to ammonia. For other classes, the effect can be seen in Table 3.

According to the normalized values for the endpoint indicators in Figure 8, treated wastewater has the largest share of environmental impacts in the class of human health impact in the WWT process. The consumed power from the biogas CHP unit has negative values, which indicates positive effects in the human health impact class. In other impact classes, the environmental effects are much less.

Table 3: Effect class weighting of South Tehran' treatment plant system using the ReCiPe 2016-midpoint method.

Effect class*	Indicator**							
	Tot.	PWW	PF	Amm	NF	CP grid	CP CHP	Cl
1	0.105878	0.227568	2.01E − 09	2.97E − 09	1.68E − 08	0.040717	−0.16287	0.000462
2	3.16E − 05	3.16E − 05	4.06E − 14	1.30E − 13	3.39E − 13	1.25E − 15	−5.01E − 15	2.44E − 10
3	0.000317	0	1.60E − 10	1.79E − 10	1.34E − 09	0	0	0.000317
4	−0.00032	0	5.16E − 12	8.05E − 12	4.30E − 11	0.000108	−0.00043	1.33E − 08
5	0.000426	0.000681	7.77E − 12	5.67E − 12	6.48E − 11	8.52E − 05	−0.00034	9.05E − 07
6	−0.00032	0	5.31E − 12	8.17E − 12	4.43E − 11	0.000108	−0.00043	2.14E − 08
7	0.004646	0.005518	4.12E − 11	1.64E − 11	3.43E − 10	0.000292	−0.00117	2.89E − 06
8	0.00067	0.00067	8.09E − 13	6.75E − 13	6.75E − 12	3.09E − 10	−1.24E − 09	4.40E − 10
9	−4.61E − 09	0	5.51E − 12	1.40E − 13	4.60E − 11	2.10E − 09	−8.41E − 09	1.64E − 09
10	0.000264	7.61E − 17	4.10E − 09	1.85E − 08	3.42E − 08	8.71E − 07	−3.49E − 06	0.000266
11	0.01196	0.01196	4.19E − 11	9.66E − 11	3.50E − 10	3.53E − 10	−1.41E − 09	6.71E − 08
12	101.1531	101.1523	3.08E − 07	1.18E − 06	2.57E − 06	7.52E − 06	−3.01E − 05	0.000798
13	0.001767	0.001766	3.82E − 09	4.98E − 09	3.18E − 08	1.42E − 09	−5.69E − 09	8.18E − 07
14	84.52448	84.52386	2.50E − 07	9.67E − 07	2.08E − 06	6.87E − 06	−2.75E − 05	0.000633
15	2.49E − 08	0	2.66E − 09	3.70E − 11	2.22E − 08	0	0	0
16	−3.23E − 07	0	5.07E − 12	1.99E − 11	4.23E − 11	1.14E − 07	−4.55E − 07	1.78E − 08
17	−0.03865	0	3.62E − 10	9.91E − 10	3.02E − 09	0.012914	−0.05166	8.88E − 05
18	−1.55E − 05	0	3.03E − 10	6.06E − 11	2.53E − 09	6.03E − 06	−2.41E − 05	2.58E − 06

*(1) global warming (kg CO2 eq), (2) depletion of the stratospheric ozone layer (kg CFC11 eq), (3) ionizing radiation (kBq Co-60 eq), (4) ozone formation, human health (kg NOx eq), (5) formation of fine particles (kg PM2.5 eq), (6) ozone formation, terrestrial ecosystems (kg NOx eq), (7) acidification of the earth (kg SO2 eq), (8) freshwater eutrophication (kg P eq), (9) marine eutrophication (kg N eq), (10) terrestrial environmental toxicity (kg 1,4-DCB), (11) environmental toxicity of fresh water (kg 1,4-DCB), (12) marine environmental toxicity (kg 1,4-DCB), (13) carcinogenic toxicity in humans (kg 1,4-DCB), (14) noncarcinogenic toxicity in humans (kg 1,4-DCB), (15) land use (m2a crop eq), (16) lack of mineral resources (kg Cu eq), (17) lack of fossil resources (kg oil eq), (18) water consumption (m3). **Tot, total; PWW, purified wastewater; PF, phosphorus fertilizer; Amm, ammonia; NF, nitrogen fertilizer; CP grid, consumed power (grid); CP CHP, consumed power (CHP); Cl, chlorine.

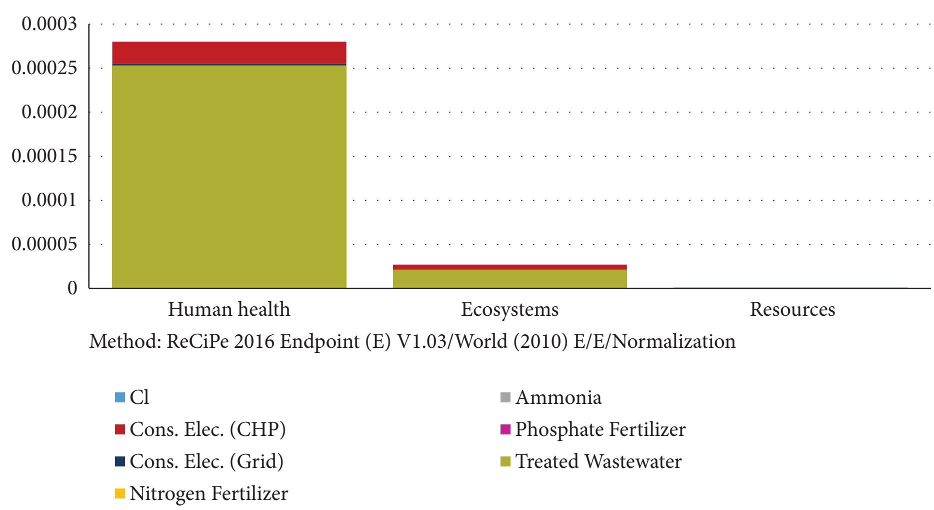

Figure 8: Normalized effect sections in the WWT process.

4. Conclusions

Environmental effects in impact classes were analyzed by using the ReCiPe 2016 method in SimaPro software. According to the treatment process analysis, the most influential factors were treated wastewater and chlorine, and the consumed power from the CHP unit has reduced effects in most classes. It has reduced the environmental impacts compared to the consumed power from the power grid. The process of WWT ultimately results in a considerable amount of treated wastewater, which will cause significant environmental impacts. According to the normalized values, marine environmental toxicity, noncarcinogenic toxicity in humans, and freshwater environmental toxicity contribute considerably to the system. Treated wastewater has the most remarkable effects on stratospheric ozone layer destruction, earth acidification, freshwater eutrophication, freshwater environmental toxicity, marine environmental toxicity, and carcinogenic toxicity and noncarcinogenic toxicity in humans. Also, it did not affect ionizing radiation, ozone formation, human health, ozone formation of terrestrial ecosystems, marine eutrophication, land use, lack of mineral resources, lack of fossil resources, and water consumption. Among the effect classes, human health is more critical because the WWT process is always associated with energy consumption, and it is not possible to save in this field, so energy consumption will be one of the influencing factors and the only way to energy saving will be to improve the technology of the treatment plant. The power consumed from the CHP unit has reducing effects on global warming, ozone formation, human health, formation of fine particles, terrestrial ecosystems, marine eutrophication, lack of mineral resources, lack of fossil resources, and water consumption.

It is recommended that situations such as the pyrolysis of digester sludge and the biological absorption of carbon dioxide from biogas be added to the current research.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] F. Daskiran, H. Gulhan, H. Guven, H. Ozgun, and M. E. Ersahin, "Comparative evaluation of different operation scenarios for a full-scale wastewater treatment plant: modeling coupled with life cycle assessment," *Journal of Cleaner Production*, vol. 341, Article ID 130864, 2022.

[2] A. Eskandari Ashgofti, M. Morovati, E. Alaiee, and K. Alavi, "Investigating the wastewater treatment system of the tehran oil industry research institute using the life cycle assessment method," *The Journal of Tolooebehdasht*, vol. 19, pp. 96–108, 2020.

[3] M. Taheriyoun and S. Moradinejad, "Reliability analysis of a wastewater treatment plant using fault tree analysis and Monte Carlo simulation," *Environmental Monitoring and Assessment*, vol. 187, pp. 4186–4213, 2015.

[4] M. Rasouli, H. Babaei, and B. Ataeiyan, "The effect of lignocellulosic waste on treatment of municipal wastewater in anaerobic digestion process," *Journal of Environmental Engineering and Science*, vol. 18, no. 2, pp. 61–69, 2023.

[5] H. Abyar, "Life cycle assessment of wastewater treatment systems: challenges and approaches," *Environmental Resources Research*, vol. 10, pp. 41–50, 2022.

[6] M. Feizi Masoule and M. Tabesh, "A review on life cycle assessment and its application in urban wastewater treatment plants," *First national conference on environmental protection and planning*, vol. 12, pp. 1–15, 2013.

[7] M. Mohammadi and E. Fataei, "Comparative life cycle assessment of municipal wastewater treatment systems: lagoon and activated sludge," *Caspian Journal of Environmental Sciences*, vol. 17, pp. 327–336, 2019.

[8] S. Renou, J. S. Thomas, E. Aoustin, and M. N. Pons, "Influence of impact assessment methods in wastewater treatment LCA," *Journal of Cleaner Production*, vol. 16, no. 10, pp. 1098–1105, 2008.

[9] A. Ding, R. Zhang, H. H. Ngo et al., "Life cycle assessment of sewage sludge treatment and disposal based on nutrient and energy recovery: a review," *Science of the Total Environment*, vol. 769, Article ID 144451, 2021.

[10] A. P. Acero, C. Rodríguez, and A. C. Changelog, "LCIA methods Impact assessment methods in Life Cycle Assessment and their impact categories," 2016, http://www.openlca.org/files/openlca/Update_info_open.

[11] L. Corominas, J. Foley, J. S. Guest et al., "Life cycle assessment applied to wastewater treatment: state of the art," *Water Research*, vol. 47, no. 15, pp. 5480–5492, 2013.

[12] J. B. Guinee, "Handbook on life cycle assessment operational guide to the ISO standards," *International Journal of Life Cycle Assessment*, vol. 7, no. 5, p. 311, 2002.

[13] M. A. Curran, "Life Cycle Assessment: a review of the methodology and its application to sustainability," *Current Opinion in Chemical Engineering*, vol. 2, pp. 273–277, 2013.

[14] E. M. M. Esteves, A. M. N. Herrera, V. P. P. Esteves, and C. D. R. V. Morgado, "Life cycle assessment of manure biogas production: a review," *Journal of Cleaner Production*, vol. 219, pp. 411–423, 2019.

[15] A. D. Singh, A. Upadhyay, S. Shrivastava, and V. Vivekanand, "Life-cycle assessment of sewage sludge-based large-scale biogas plant," *Bioresource Technology*, vol. 309, Article ID 123373, 2020.

[16] G. Finnveden, M. Z. Hauschild, T. Ekvall et al., "Recent developments in life cycle assessment," *Journal of Environmental Management*, vol. 91, pp. 1–21, 2009.

[17] A. Kylili, E. Christoforou, and P. A. Fokaides, "Environmental evaluation of biomass pelleting using life cycle assessment," *Biomass and Bioenergy*, vol. 84, pp. 107–117, 2016.

[18] D. W. Pennington, J. Potting, G. Finnveden et al., "Life cycle assessment Part 2: current impact assessment practice," *Environment International*, vol. 30, no. 5, pp. 721–739, 2004.

[19] F. C. Ertem, J. Martínez-Blanco, M. Finkbeiner, P. Neubauer, and S. Junne, "Life cycle assessment of flexibly fed biogas processes for an improved demand-oriented biogas supply," *Bioresource Technology*, vol. 219, pp. 536–544, 2016.

[20] M. Bengtsson, M. Lundin, and S. Molander, *Life Cycle Assessment of Wastewater Systems-Case Studies of Conventional Treatment, Urine Sorting and Liquid Composting in Three Swedish Municipalities*, Chalmers University of Technology, Gothenburg, Sweden, 1997.

[21] D. Blanco, S. Collado, A. Laca, and M. Díaz, "Life cycle assessment of introducing an anaerobic digester in a municipal wastewater treatment plant in Spain," *Water Science and Technology*, vol. 73, no. 4, pp. 835–842, 2016.

[22] B. Liu, Q. Wei, B. Zhang, and J. Bi, "Life cycle GHG emissions of sewage sludge treatment and disposal options in Tai Lake Watershed, China," *Science of the Total Environment*, vol. 447, pp. 361–369, 2013.

[23] J. B. Guinee, "Handbook on life cycle assessment operational guide to the ISO standards," *International Journal of Life Cycle Assessment*, vol. 7, no. 5, pp. 311–313, 2002.

[24] M. A. Thomassen, K. J. van Calker, M. C. J. Smits, G. L. Iepema, and I. J. M. de Boer, "Life cycle assessment of conventional and organic milk production in The Netherlands," *Agricultural Systems*, vol. 96, no. 1-3, pp. 95–107, 2008.

[25] ecoinvent, "Database-ecoinvent," 2024, https://ecoinvent.org/database/.

[26] A. Ciroth, J. Hildenbrand, and B. Steen, "Life cycle costing," *Sustainability Assessment of Renewables-Based Products*, pp. 215–228, 2015.
[27] A. Hélias and R. Servien, "Normalization in LCA: how to ensure consistency?" *International Journal of Life Cycle Assessment*, vol. 26, no. 6, pp. 1117–1122, 2021.
[28] H. Gjalt and V. O. Lauran, *Background Review of Existing Weighting Approaches in Life Cycle Impact Assessment (LCIA)*, European Union, Luxembourg, 2011.
[29] I. T. Herrmann and A. Moltesen, "Does it matter which Life Cycle Assessment (LCA) tool you choose?–a comparative assessment of SimaPro and GaBi," *Journal of Cleaner Production*, vol. 86, pp. 163–169, 2015.
[30] M. Goedkoop and R. Spriensma, "The eco-indicator 99: a damage oriented method for life cycle impact assessment,"Methodology Report, Amersfoort, The Netherlands.
[31] M. A. J. Huijbregts, Z. J. N. Steinmann, P. M. F. Elshout et al., "ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level," *International Journal of Life Cycle Assessment*, vol. 22, no. 2, pp. 138–147, 2017.
[32] E. Buonocore, S. Mellino, G. De Angelis, G. Liu, and S. Ulgiati, "Life cycle assessment indicators of urban wastewater and sewage sludge treatment," *Ecological Indicators*, vol. 94, pp. 13–23, 2018.
[33] J. Cartes, P. Neumann, A. Hospido, and G. Vidal, "Life cycle assessment of management alternatives for sludge from sewage treatment plants in Chile: does advanced anaerobic digestion improve environmental performance compared to current practices?" *Journal of Material Cycles and Waste Management*, vol. 20, no. 3, pp. 1530–1540, 2018.
[34] I. Lanko, L. Flores, M. Garfí et al., "Life cycle assessment of the mesophilic, thermophilic, and temperature-phased anaerobic digestion of sewage sludge," *Water*, vol. 12, no. 11, p. 3140, 2020.
[35] H. Yoshida, J. Clavreul, C. Scheutz, and T. H. Christensen, "Influence of data collection schemes on the Life Cycle Assessment of a municipal wastewater treatment plant," *Water Research*, vol. 56, pp. 292–303, 2014.
[36] K. Patel and S. K. Singh, "A life cycle approach to environmental assessment of wastewater and sludge treatment processes," *Water and Environment Journal*, vol. 36, no. 3, pp. 412–424, 2022.