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Assessing the Environmental Implications of Water and Wastewater Production Using Life Cycle Assessment

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ABSTRACT

In the face of increasing global challenges, such as water scarcity, population growth, and environmental degradation, sustainable management of water resources and wastewater treatment is a major concern. However, sometimes the potential impact of water system management on the environmental implications contained in the production process of water and waste treatment systems is omitted. This study sought to assess the environmental efficacy of an integrated water supply and wastewater system in the Semarang City. The secondary objectives of the study were to ascertain the extent to which each stage of the system contributed to the impact categories that were analyzed. Life cycle assessment is a method to evaluation of the environmental impacts associated with water resource and wastewater management, using 1 m^3 as functional unit. The stages of water use are not examined in this study. Another restriction is the absence of information about the city's untreated wastewater quantities' final destination. Water treatment plant include water withdrawal and water distribution are most impacted under the climate change environmental impact category and other impact that assess until 99%. In seven of the eight impact categories examined, power consumption is the most impactful input.

Keywords: environmental impact, water system management, life cycle assessment, Semarang city.

INTRODUCTION

In the face of increasing global challenges, such as water scarcity, population growth, and environmental degradation, sustainable management of water resources and wastewater treatment is a major concern [Yu et al., 2023]. However, sometimes missed regarding the potential impact of water system management on the environmental implications contained in the production process of water and waste treatment systems. In the collective endeavor to secure access to potable water while mitigating ecological repercussions, the adoption of rigorous methodologies for comprehensively evaluating the complete life cycle of water and waste infrastructure emerges as imperative; the sustainable management of water resources has become a paramount concern [Maheshwari et al., 2023]. The urgency of this inquiry is underscored by the escalating global strain on water resources, a situation further compounded by elements like climate change and swift urbanization. Both conventional and contemporary methods of water and waste management, despite effectively meeting immediate requirements, frequently yield unanticipated environmental ramifications. Water serves as a critical element in supporting life and a constraint on socioeconomic progress; therefore, the measures aimed at achieving efficient and environmentally friendly water resource management are imperative in light of these conditions [Syafrudin et al., 2024].

Life cycle assessment (LCA) is a method of evaluating the environmental impacts associated with water resource and wastewater management. Throughout the life cycle of the analyzed product, LCA is capable of calculating and evaluating the inflow and egress of materials from a production system as well as estimating its potential environmental impacts. Therefore, it has the potential to aid in the detection of material processes and flows that possess a higher capacity to cause environmental harm [Maheshwari et al., 2023]. When examining urban water systems, the implementation of LCA may take into account various system boundaries. Regarding the system boundary, Lehtoranta et al. [2022] examined only the water treatment phase. Additionally, a number of studies have been devoted to the analysis of wastewater treatment, with objectives ranging from identifying and quantifying the environmental impacts of the wastewater plant to assessing its environmental performance [Gómez-Monsalve et al., 2022; Sala-Garrido et al., 2023; Zhao et al., 2023] and conducting a comparative analysis of various treatment systems or technologies to determine which has the smallest environmental impact [Boldrin et al., 2022; Panagopoulos & Giannika, 2022; Zahmatkesh et al., 2023].

Moreover, LCA analyses also pertain to entire wastewater treatment. The environmental performance of these systems is assessed through LCA in these instances, which involve the evaluation of an integrated wastewater system, as was the case with the assessments conducted in Italy [Arfelli et al., 2022], Brazil [Lima et al., 2022], Portugal [Boldrin & Formiga, 2023], which demonstrated that water withdrawal and water treatment contributed more to the majority of environmental impact categories due to the electricity consumption associated with these processes. Tong et al. [2019] explained that stages of wastewater treatment and disposal made substantial contributions to the categories of eutrophication and marine ecotoxicity. According to the findings of Cardoso et al. [2021]; Mannan and Al-Ghamdi [2022], the primary environmental consequences falling under the category of global warming stem from the energy-intensive phases of distribution, collection, pumping, and wastewater treatment plants (WWTP). [Al-Hazmi et al., 2023]; Pesqueira et al. [2020] determined that wastewater treatment contributed the most to the impact categories examined in their study, with wastewater collection and water distribution following suit. Furthermore, the system's electricity consumption accounted for the greatest proportion of the analyzed impact categories. According to the findings of Shahedi et al. [2020], the most significant environmental consequences of the system were associated with the water treatment facilities that operated at high electricity consumption and disposed of primary treatment effluent. Over an extended period, LCA has been a valuable tool for evaluating the anticipated environmental effects and efficacy of water and wastewater systems. Typically, the scrutinized systems feature wastewater treatment facilities employing active sludge systems, anaerobic digesters, biological reactors, and UV treatment technology performance [Gómez-Monsalve et al., 2022; Sala-Garrido et al., 2023; Zhao et al., 2023].

Nevertheless, the research pertaining to effluent treatment technologies that utilize pond systems remains limited. In order to eliminate pathogens, organic matter, and pollutants from raw effluent, pond systems employ physical and biological processes while remaining expansive and shallow. Implemented extensively in developing nations with suitable space for its installation, this treatment method is characterized by its simplicity [Hardyanti et al., 2023]. By utilizing a pond system for wastewater treatment, this study sought to assess the environmental efficacy of an integrated water supply and wastewater system in Semarang City. The secondary objectives of the study were to ascertain the extent to which each stage of the system contributed to the impact categories that were analyzed. This study is unique in that it applies LCA to a pond-based integrated water supply and effluent system. Furthermore, this analysis yields significant data that may be utilized in subsequent investigations or in implementing management strategies for the urban water systems exhibiting this attribute.

MATERIAL AND METHOD

LCA was conducted utilizing data from the Ecoinvent database (3.7.1) and the SimaPro software (version 8.0.3) in conformance with the ISO 14040 and ISO 14044 standards. This section should contain an overview of the attributes of the municipal water and wastewater system under analysis, as well as the essential data required to implement LCA.

Description of study existing

The city of Semarang is located in Central Java, Indonesia (Figure 1) and has an estimated population of 1,693,035 people. Water supply and waste water services are provided in an integrated manner by the Semarang City Environmental Service and the Regional Drinking Water Company (PDAM) Tirta Moedal Semarang City. The entire urban population of the municipality is served by water supply services. Approximately 98.5% of the city water is supplied from surface sources in artesian wells and springs (Kalidoh Besar, Ancar, Moedal Besar, Moedal Kecil, Lawang, Lawang II). This water is transported via a raw water transportation system consisting of a 35 km long pipe and two lifting stations to the water treatment plant (WTP), which is then processed by ponds (Coagulation and Flocculation, Sedimentation, Filtration, Reservoir). After processing, water is supplied through the distribution network 509 km long pipe, 4 pump stations to supply water to each household. Meanwhile, the wastewater collection network consists of 95 km of treated pipes in Semarang City, which consists of two sets of ponds (Grit Chamber, Grease Trap, Aeration, Filtration). In the grit chamber, domestic wastewater is collected and then before entering the WWTP, the wastewater passes through a grease trap, which functions to filter out large solids. Then, the wastewater is channeled into aeration where it is treated with the addition of bacteria and oxygen which functions to reduce existing pollutants. Before flowing into the effluent tank, the treated wastewater is filtered again through a filtration tank, to reduce the solids that are still present. Then, the wastewater flows into the effluent tank where chlorine is added to this tank to kill bacteria that are still in it. It is hoped that waste water can meet the required quality standards. Next, the wastewater is channeled into the fish pool as an indicator that the it is suitable for disposal into the environment towards the Tapak River. With its capacity, the wastewater network can accommodate around 63% of the effluent produced within the

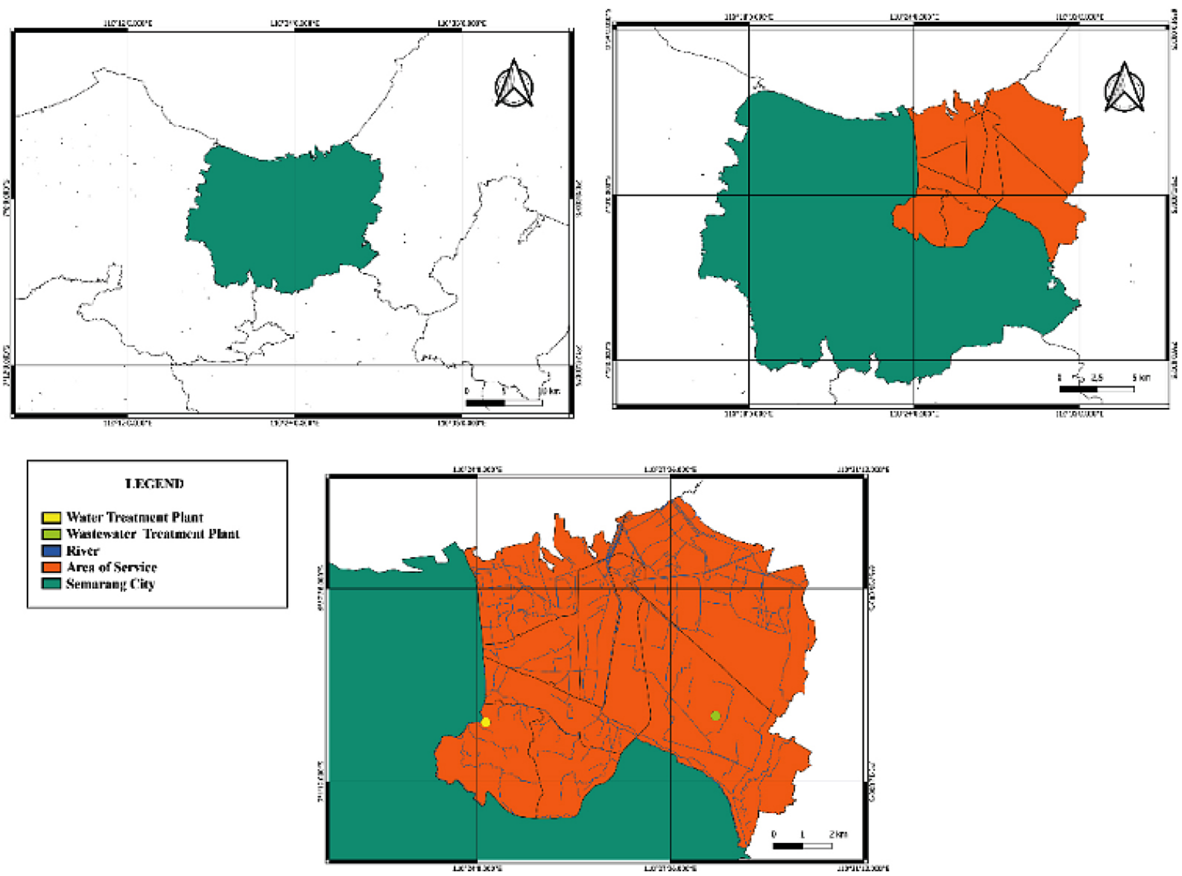

Figure 1. Analysis location at Semarang City

municipality's urban zone. An estimated 79.6% of this volume is treated, giving the municipality a treatment index of 50% for effective effluent.

System boundaries and functional unit

The volume of 1 m^3 of purified wastewater or 1 m^3 of potable water is accounted for as the functional unit for the application of LCA to the water supply and wastewater system in Semarang City. The operational unit employed is 1 m^3, which is the format utilized for official PDAM Tirta Moedal data pertaining to effluent and water supply systems. Additionally, this functional unit is utilized in other studies in the field, which will enable future comparisons of systems and facilitate the interpretation of data. The values per functional unit for the wastewater system were determined solely on the basis of the purified wastewater volume. This study examined integrated water supply and wastewater systems, as illustrated in Figures 2 and 3. The stages of water withdrawal, treatment, water distribution, wastewater collection, and wastewater treatment constitute the system boundary. Apart from the functioning of the system, the pipelines utilized during the withdrawal, water distribution, and wastewater collection phases were also taken into account in this analysis.

Life cycle inventory

According to operational data for 2021 and 2022, system operational data was obtained from the PDAM Tirta Moedal Website and the Semarang City Environmental Service. Supplementary data was gathered from published research and special government reports pertaining to

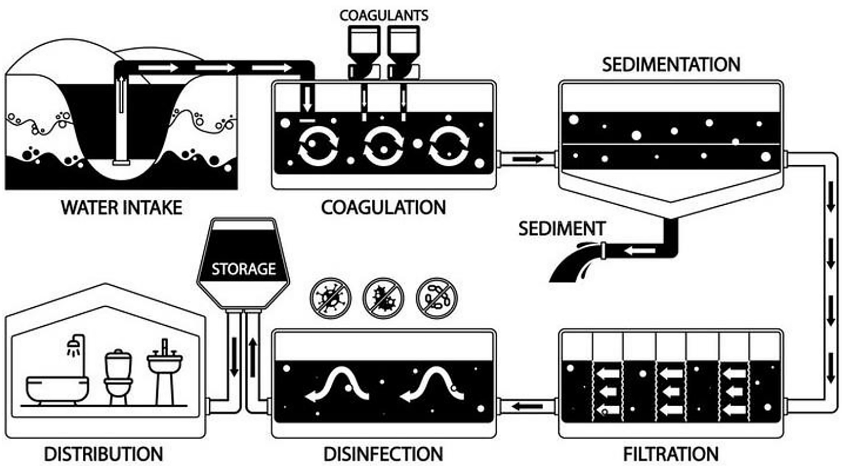

Figure 2. Flow scheme of investigated WTP at PDAM Tirta Moedal

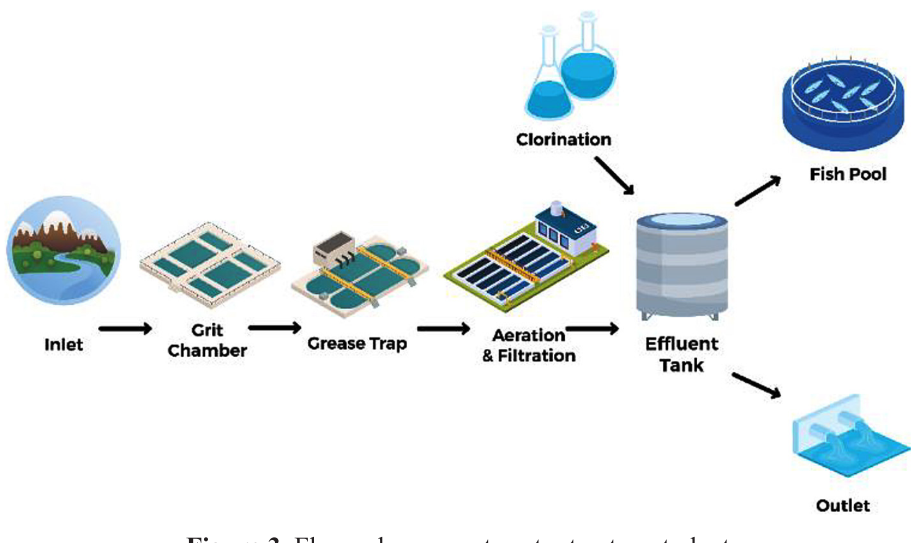

Figure 3. Flow scheme wastewater treatment plant

sanitation. Table 1 provides a compilation of inventory data and their corresponding sources pertaining to 1 m^3 of treated effluent. The electricity consumption of each stage of the water supply and wastewater system under analysis was furnished by PDAM Tirta Moedal. To calculate the electricity consumption per functional unit, the quantity of electricity utilized was divided by the volume of water produced at each stage of the system (water withdrawal, water treatment, distribution, and effluent collection). When precise data were unavailable for certain components of each phase, average electricity consumption data were utilized. The quantities reported by the system operator for the year 2022 pertain to the chemical consumption during the water treatment phase. In the same year, the consumption per 1 m^3 functional unit was calculated by dividing the quantity of chemical utilized by the volume of treated water. The chemical products utilized in water treatment were obtained from other municipalities and conveyed to the WTP over distances of 253 km (aluminum sulfate) and 375 km (fluosilicic acid, sodium hypochlorite, and sodium carbonate). Furthermore, the transport is accounted for in the analysis.

In order to streamline the analysis, it was assumed that all pipes were composed of PVC. The raw water pipelines had a mass of 14 kg/m, while the pipes of the water-distribution and wastewater-collection networks had a mass of 4 kg/m. The database Ecoinvent 3.7.1 was queried for background information, from which European data were selected. In the absence of these particular data, global (GLO) data were utilized. Table 1 provides a description of the procedures utilized in Ecoinvent. The information system operator provided was consulted regarding wastewater treatment facilities; however, the emissions data were not obtainable. The methods recommended by the intergovernmental panel on climate change (IPCC) were thus utilized to estimate the methane emissions from wastewater treatment basins. This estimation is predicated on prior investigations of similar kinds.

Life cycle impact assessment

In consideration were the subsequent impact categories: climate change, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, ozone depletion, terrestrial acidification, and terrestrial ecotoxicity. The potential impact analysis of WTP and WWTP takes into account significant factors including terrestrial acidification, terrestrial ecotoxicity, climate change, and fossil fuel depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, and ozone depletion. The significance of these factors lies in the potential health and environmental consequences that may result from the utilization and production, distribution, as well as application of energy and compounds in the operation of these facilities. This analysis offers a comprehensive perspective on the environmental and health consequences linked to WWTP and WTP methods, encompassing concerns such as toxicity for ecosystems and risk to global climate change. Table 2 provides descriptions of the impact categories that were chosen for the ReCiPe method. Applying the cumulative energy demand method—which measures the direct and indirect primary energy consumption of a product over its entire life cycle—the energy impacts of the analyzed scenarios were computed. Non-renewable (fossil, nuclear, and primary forest) and renewable (solar, wind, biomass, etc.) primary energy sources are included in this analysis.

RESULT AND DISCUSSION

Environmental impact assessment

A comparison of the environmental impact levels associated with each analyzed scenario for treating raw water and wastewater is conducted by associating each scenario with a corresponding impact category. This comparison enables the determination of the scenario that causes the least detrimental effect on the environment. The values corresponding to the impact categories for each impact scenario are displayed in Table 3 and Figure 4, illustrating the proportional impact of each system stage on the overall impacts of each category. The water withdrawal system has the highest relative contribution, followed by the water treatment plant and the wastewater treatment plant. The water distribution system has the lowest relative contribution. The water withdrawal system is the largest contributor to four impact categories. The amount of electricity needed to ensure the extraction and transportation of raw water is correlated with the high proportional contribution of water withdrawal. Withdrawal uses the most electricity per cubic meter of generated drinking water of all the processes examined.

Table 1. Life cycle inventory WTP and WTPP

Input	Amount	Unit	Source
Water withdrawal			
Electricity (BR)	1.021	kWh/m^3	PDAM Tirta Moedal
Extrusion, plastic pipes (GLO)	0.00242	kg/m^3	[Rebello et al., 2023; Santos et al., 2023]
Water treatment plant		kWh/m^3	PDAM Tirta Moedal
Electricity (BR)	0.00654	kWh/m^3	~II~
Aluminum sulfate in a solution state (GLO) of 4.33% aluminum, devoid of water.	0.000431	kg/m^3	~II~
Liquid poly aluminium chloride	0.0065	kg/m^3	~II~
Sodium hypochlorite synthesis, 15% solution state (GLO) product	0.000639	kg/m^3	~II~
Fluosilicic acid, without water, in 22% solution state (GLO)	0.0009631	kg/m^3	~II~
Sodium carbonate/soda ash (GLO)	0.0592	kg/m^3	~II~
Transport, freight, lorry 16–32 metric ton, (GLO)	0.05662	$t\ km/m^3$	~II~
Water distribution			
Electricity (BR)	0.5312	kWh/m^3	
Extrusion, plastic pipes (GLO)	0.0413	kg/m^3	[Rebello et al., 2023; Santos et al., 2023]
Wastewater collection			
Electricity (BR)	0.214	kWh/m^3	Existing Condition
Extrusion, plastic pipes (GLO)	0.0345	kg/m^3	Existing Condition
Wastewater treatment plant			
BOD input	0.005864	$kg\ DBO/m^3$	Existing Condition
Methane emission	0.12864	$kg\ CH_4/m^3$	Existing Condition
BOD output	0.2853	$kg\ DBO/m^3$	Existing Condition
Dried sludge	59.22	t/d	[Daskiran et al., 2022]
N_2O	2.45	g	~II~
CO	0.0844	mg	~II~
TOC	0.00184	mg	~II~
SO_2	0.00918	mg	~II~
NO_x	0.00147	mg	~II~

The cumulative energy demand analysis supports this, since withdrawal is the system step that contributes most proportionately to this category.

CC has the largest relative contribution to WTP. This is because primary contributions come from the transfer of chemical items from the point of sale to the WTP and the usage of sodium carbonate and Lorry with refrigeration machine in water treatment. With a respective 87% relative contribution, wastewater collecting networks and have the largest FEU rates. Since the pipes are manufactured, these system processes have a major impact on the category of FET. Wastewater and water treatment plants contribute to several environmental impact categories due to the processing technologies employed and the level of operational data available. The energy intensity of specific treatment methods, the choice of energy sources, and the emissions generated by chemical production all influence climate change impact. Similarly, nutrient removal efficiency and discharge levels affect freshwater eutrophication. Water consumption during treatment and losses in distribution systems contribute to water scarcity. The use of chemicals in treatment disinfection by products impacts the human toxicity potential. Additionally, the emissions from energy production and chemical processes influence acidification, while the use of ozone-depleting substances in disinfection affects ozone depletion. To minimize these environmental impacts, implementing efficient and sustainable technologies alongside advanced monitoring and data analysis is crucial [Priyambada et al., 2023]. This enables optimized

Table 2. Impact category description

Impact category	Description	Characterization factor	Indicator	Unit
Climate change	Evaluates the potential ramifications of emissions of greenhouse gases (GHGs). GHG increase global warming by trapping infrared radiation emitted by the Earth's surface in the atmosphere.	In global warming potential (GWP), the impact of 1 kg of any greenhouse gas (GHG) is contrasted with that of 1 kg of CO^2.	Multiplying the bulk of each greenhouse gas released by its corresponding GWP	kg CO_{2} Eq
Fossil depletion	Assesses the depletion potential of fossil fuels. Defined as the ratio of the heating value of petroleum to that of any fossil fuel with a higher heating value.	The concept of fossil fuel potential (FFP) assesses the relative thermal capacity of fossil fuels in comparison to oil.	Multiplying the collected mass of all fossil fuels by their corresponding FFP	kg oil-eq
Freshwater ecotoxicity	Assesses the ecological toxicity of substances discharged into the environment and subsequently entering freshwater ecosystems. When evaluating the impact of a chemical release, comparisons are made to the impact of 1,4-dichlorobenzene, taking into account fate, exposure, and effect parameters. Species extinction may result in freshwater ecosystems.	By comparing the impacts of chemical species to those of 1,4-DCB and taking into account fate and exposure parameters, interim and recommended CFs are established.	The sum of the masses of all discharged species multiplied by their respective CF	kg 1.4 DCB-eq
Freshwater eutrophication	Assesses the potential consequences of discharged nutrients into freshwater ecosystems. Algae blooms and a reduction in dissolved oxygen levels are consequences of nutrient concentration increases in aquatic ecosystems. Eutrophication results in the extinction of species.	By analyzing the mass of algae generated in accordance with its molecular composition (Redfield Ratio), CF compares the potential impact of species containing nitrogen or phosphorous.	Multiplying the total mass of all discharged species by their respective CF	kg P-eq
Human toxicity	Assesses the susceptibility of humans to the diseases associated with environmental substances that have been absorbed by the body. A comparison is made between the impact of any chemical release and that of 1,4 dichlorobenzene, taking into account fate, exposure, ingestion fraction, and effect parameters. Both carcinogenic and non-carcinogenic consequences on human health are possible.	Comparing the effects of chemical species to those of 1,4-DCB while evaluating recommended and interim CFs in detail, taking into account fate, exposure, and ingestion fraction parameters	CF is calculated by multiplying the sum of the masses of all released species.	kg 1.4 DCB-eq
Ozone depletion	Determines the quantity of stratospheric ozone that can be destroyed by a substance containing chlorine or bromine atoms. These recalcitrant substances, characterized by their extended atmospheric lifetimes, are the origins of chlorine and bromine that reach the stratosphere. Life on Earth is shielded from the Sun's hazardous ultraviolet radiation by the ozone layer.	CF is calculated by comparing the ozone degrading potential of chemical species to that of CFC-11, with the CF being determined by the number of chlorine atoms in chlorofluorocarbons (CFC) and bromine atoms in halons.	CF is calculated by multiplying the sum of the masses of all released species.	kg CFC-11-eq
Terrestrial acidification	Assesses the quantity of inorganic substances deposited in the environment, which contributes to acid rain and soil acidification. Variations in acidity levels have the potential to induce alterations in the distribution of species and inflict harm upon civil infrastructure.	GEOS-Chem models are utilized to forecast alterations in acid deposition caused by modifications in air emissions of NOx, NH_3, and SO_2.	The sum of the masses of all discharged species multiplied by their respective CF	kg SO_2-eq
Terrestrial ecotoxicity	Assesses the potential repercussions of chemical discharges that enter terrestrial ecosystems. In evaluating the impact of a chemical release, its effects are contrasted with those of 1,4-dichlorobenzene, taking into account fate, exposure, and effect parameters. Species loss in terrestrial ecosystems may result.	Comparing the impacts of chemical species to those of 1,4-DCB while taking into account recommended and interim CFs, fate and exposure parameters	Multiplying the total mass of all discharged species by their respective CF	kg 1.4 DCB-eq

Table 3. Result impact assessment

Impact category	Impact assessment result	
	Unit	Total
Climate change (CC)	kg CO_2 eq	1.97E+03
Ozone depletion (ODP)	kg CFC11 eq	7.29E-04
Terrestrial acidification (TA)	kg SO_2 eq	6.95E+00
Freshwater eutrophication (FEU)	kg P eq	1.18E+00
Terrestrial ecotoxicity (TE)	kg 1.4-DCB	6.20E+03
Freshwater ecotoxicity (FET)	kg 1.4-DCB	5.40E+02
Human toxicity (HT)	kg 1.4-DCB	6.15E+01
Fossil depletion (FD)	kg oil eq	4.34E+02

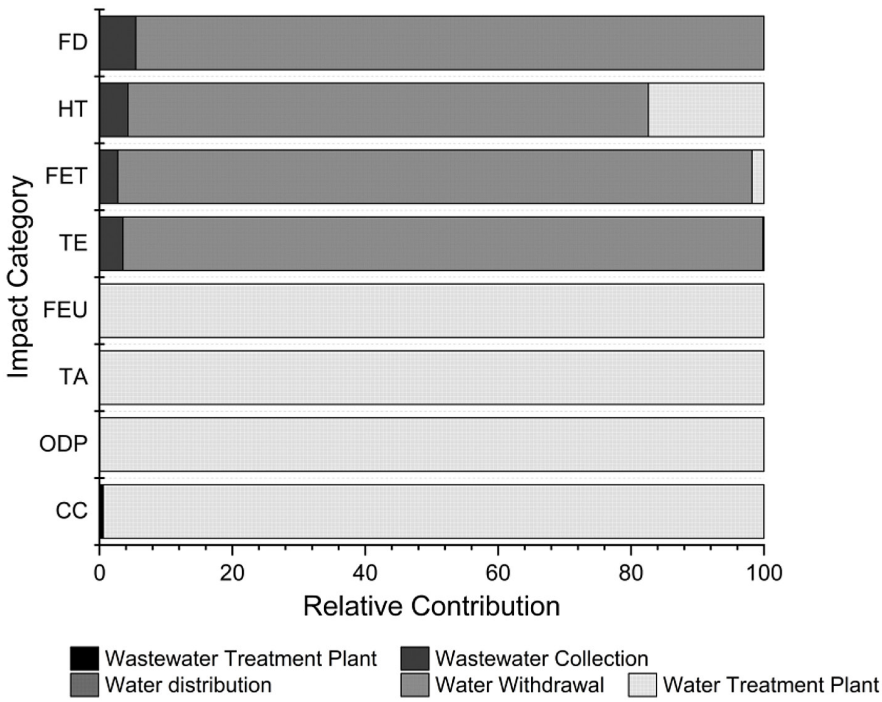

Figure 4. Relative impact contribution

processes, reduced resource utilization, and a lower environmental footprint for this essential service.

Figure 5 illustrates each input and output group's relative contribution for each effect category. The analysis of every input group reveals how electricity affects the environmental effects of urban water and wastewater systems. The largest contribution from electricity goes into the following categories: FD (61%), FET (95%), FEU (100%), HT (97%), ODP (100%), FEU (100%), TA (100%), and TE (53%). The utilization of electricity produced by thermoelectric plants, which accounted for 23% of the energy mix in the Semarang City region in 2022, is primarily responsible for these high contribution levels. Of this, 14.6% is produced by burning fossil fuels, while 8.9% is produced by burning biomass, wind, biogenic shallow coal, and coal. The methane emissions of the wastewater treatment plant account for 95% of the global warming. Fluosilicic acid (fluoridation), sodium hypochlorite (disinfection), aluminum sulfate (coagulant), and sodium carbonate (pH adjustment) are the chemicals used by the WTP to treat the water. The intake of calcium carbonate is the primary reason for highest relative contribution of these compounds in the effect categories of FET (5%), TE (45%), and FD (32%). Lastly, in the FD and TE effect categories, the pipelines utilized for wastewater collection, water distribution, and withdrawal have the largest

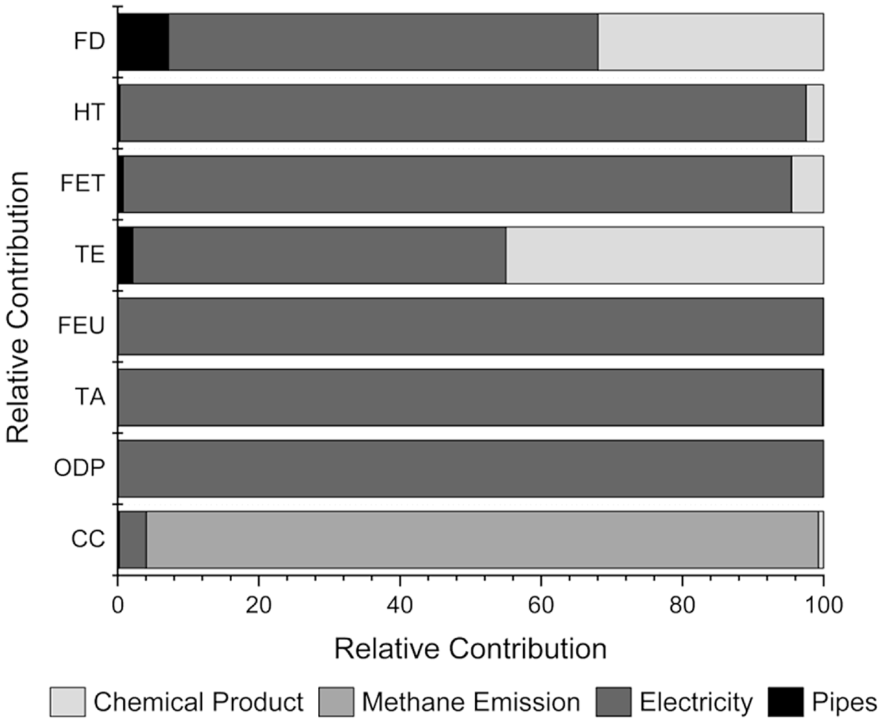

Figure 5. Relative impact category from input and output

relative contributions (7% and 2%, respectively).The largest contributor to possible environmental effects, according to other research that used LCA on urban water systems, was electricity use. Electricity makes a substantial contribution, even with the technological and methodological variations in these research (e.g., treatment technology, system boundaries, and environmental effect assessment techniques) [Islam, 2023; Karadimos & Anthopoulos, 2023; Samitha Weerakoon & Assadi, 2023; Singh et al., 2023]. Orography and the separation between the water withdrawal and consumption points influence the amount of electricity used in urban water systems [Kayiranga et al., 2024]. An analysis of the environmental burdens of the analyzed urban water and wastewater system revealed that the largest contributor to these burdens was electricity consumption. This finding supports the use of an electricity consumption index to measure the environmental performance of urban water systems in Brazil and Italy [Arfelli et al., 2022; Boldrin et al., 2022].

Study limitation

The stages of water use are not examined in this study. This restricts the study because the inputs (such electricity) might have improved the outcomes in the impact categories that were examined. Another restriction is the absence of information about the final destination of the city's untreated wastewater quantities. A more thorough evaluation of the system under study's environmental impact will result from the inclusion of this data in the analysis. Moreover, examining the environmental effects of producing water and wastewater through the perspective of LCA is the primary goal of this study. The researchers remained committed to being clear and precise when discussing the fundamental components of the environmental repercussions of producing water and wastewater, which is why they decided against discussing separate sections on scenario and sensitivity analyses. Sensitivity and scenario analyses are useful methods frequently employed in research to examine the robustness and variability of findings under various scenarios or hypotheses. Nonetheless, the authors may decide to give priority to a clearer, more straightforward analysis of the effects of the life cycle on the environment in this specific situation. The authors indicate a purposeful focus on providing a coherent narrative based on important LCA conclusions relating to water and wastewater generation by purposefully leaving out parts that discuss scenario and sensitivity analysis.

CONCLUSIONS

LCA is used to assess the environmental performance of a water supply and wastewater treatment system that uses a pond system to treat wastewater. Water removal contributes the most to possible environmental effects among the stages under analysis till 1.97E+03 kg CO_2 eq. WTP includes water withdrawal and water distribution are most impacted under the CC until 99% and other environmental impact category and other impact that assess. This is because primary contributions come from the transfer of chemical items from the point of sale to the WTP and the usage of sodium carbonate and Lorry with refrigeration machine in water treatment. In seven of the eight impact categories examined, power consumption was shown to be the main system input and output flow factor that could have an adverse effect on the environment. The largest contribution from electricity goes into the following categories: FD (61%), FET (95%), FEU (100%), HT (97%), ODP (100%), FEU (100%), TA (100%), and TE (53%). The utilization of electricity produced by thermoelectric plants, which accounted for 23% of the energy mix in the Semarang City region in 2022, is primarily responsible for these high contribution levels. In the CC category, the methane emissions from WWTP are the primary cause of environmental effects.

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