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Life Cycle Environmental Implications of Wastewater Treatment at an Academic Institution

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ABSTRACT

This study performs a life cycle assessment (LCA) on the wastewater treatment operations at Sebelas Maret University in Surakarta, Indonesia, with the goal of systematically evaluating the environmental impacts associated with its processes. LCA serves as a comprehensive method for assessing environmental impacts across all stages of a product's life cycle, which includes goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. Utilizing this methodology, our analysis categorizes environmental impacts into three significant domains: human health, ecosystem quality, and resource depletion. The findings indicate that human health is the most impacted category, showing an effect of 0.275 disability-adjusted life years (DALY) -equivalent units. Resource depletion follows, measured at 0.193 DALY-equivalent units, and non-renewable energy consumption is quantified at 0.0214 DALY-equivalent units. To address these impacts, the study proposes several improvement strategies, such as adopting more sustainable clean water treatment technologies, capturing and utilizing methane gas through anaerobic digestion, and establishing green spaces for CO_2 sequestration. These strategies aim to reduce the environmental footprint of the wastewater treatment process, moving towards more sustainable management practices.

Keywords: life cycle assessment, wastewater treatment plant, impacts.

INTRODUCTION

Wastewater treatment sector is known to potentially contribute to eutrophication, a condition where water bodies experience elevated levels of organic matter and nutrients. Key nutrients such as nitrate and orthophosphate can lead to eutrophication, causing a rapid increase in phytoplankton populations [1]. The wastewater treatment plant (WWTP), inaugurated in 2017 on the Sebelas Maret University (UNS) campus, serves as a pioneering model in waste management, being one of the first of its kind. Given its significant processing capacity of 1,293 m^3/day, it is imperative to analyze this facility's processing cycle and environmental impact using the life cycle assessment (LCA) method. LCA is a comprehensive analytical tool designed to evaluate the environmental impacts of a project, product, or service [2]. This method facilitates identifying potential waste generation, energy consumption, and raw material requirements during product processing [3, 4]. Furthermore, LCA is instrumental in assessing a company's environmental performance, aiding in identifying and implementing environmental improvements [5, 6]. Life cycle assessment in general is a tool or method for analyzing environmental loads at all stages in the product life cycle starting from resource extraction, through the production process of materials, product parts and the product itself, and the use of the product until it is disposed of (either by reuse, recycling or final disposal), in other words cradle to grave [7, 8]. More broadly, LCA is employed to analyze environmental burdens at every stage of a product's life cycle, from resource extraction to the final product disposal, encompassing recycling and reuse that a process known as 'cradle to grave' [10, 11]. This assessment spans three critical dimensions: economic, environmental, and social, underpinning sustainable development in ecological, economic security, and social welfare terms. In a technical sense, it significantly influences resource utilization for generating and renewing activities [9].

LCA is a methodology used for environmental impact assessments associated with products. The initial step in LCA involves compiling and inventorying the inputs and outputs related to the product's lifecycle. This approach is also valuable in assessing potential contributions to global warming from each stage of biomass utilization. The 'cradle to grave' concept in LCA begins with the extraction of raw materials and concludes when all materials are returned to the earth. LCA enables the estimation of cumulative environmental impacts from all stages of a product's life cycle, thus highlighting which stage has the greatest environmental impact. This method has been extensively applied in assessing the environmental impacts of urban water infrastructure, including WWTPs [10].

Research on the life cycle of water treatment, particularly in the wastewater sector, has been conducted in China. This research utilized a process-based and input-output-based LCA, employing the Eco-indicator 99 method. However, it focused solely on energy consumption as the sole parameter for evaluating the project, thus limiting the assessment to the impact of energy use [11]. A comparable study was undertaken in Spain, where LCA was applied to different scenarios of wastewater utilization, with a specific emphasis on toxicity-related effects [12]. Given these precedents, there is a clear need for research that more comprehensively evaluates the life cycle impacts arising from domestic wastewater treatment activities. Such research could effectively utilize SimaPro 9.1.0.11 software. The research methodology would encompass various stages, including data collection, processing with LCA. Another study proposes a model that is both process and input-output based for LCA [5, 13, 14, 15], yet it again restricts its focus to energy consumption as the only parameter. This research aims to integrate quantitative data on wastewater discharge, water quality, chemical usage, and electrical energy consumption. It employs the Eco-indicator 99 to examine 11 categories of environmental impacts.

MATERIALS AND METHODS

Jebres Village is a village located in Jebres District, Surakarta City with the largest population of 32,974 people, there is no sewerage piping service [16]. Remarkably, this village lacks a sewerage piping service. In Jebres, one finds Sebelas Maret University, the largest university in Surakarta. The university, along with other buildings in the area, relies on on-site disposal systems for wastewater management. These systems mainly consist of septic tanks with periodic drainage. Additionally, waste from bathrooms, washing areas, and places of worship is directly discharged into building drainage channels. These channels not only receive waste from the university but also from residents across various parts of the Jebres sub-district. Eventually, this waste empties into the Bengawan Solo River, leading to a decline in both the quality and quantity of water in the river. This situation is particularly concerning given that the Bengawan Solo River is a crucial source of raw water for the community, especially as the demand for clean water sources increases. To address these environmental and public health concerns, a wastewater treatment plant was established on the campus in 2017. This WWTP represents an environmentally sound solution for treating domestic wastewater in both the university and the wider Jebres area. However, it is important to note that wastewater treatment plants can impact the environment, potentially emitting significant amounts of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrogen oxides (N_2O) [17]. Estimates indicate that methane emissions from the wastewater sector have increased by about 20% from 2005 to 2020. Furthermore, by 2020, the wastewater sector was responsible for generating 3% of total nitrogen oxide emissions. Notably, emissions from the wastewater sectors in India, China, America, and Indonesia account for approximately 50% of the global nitrogen oxides emitted from wastewater, with an expected increase of about 13% from 2005 to 2020 [18].

This study evaluates the environmental impact caused by processing domestic wastewater at the WWTP using the LCA method. The data encompass the burden of industrial wastewater treatment and fuel consumption in the operation of the wastewater treatment building installation. Variables in this study are categorized into independent and dependent types. The independent variables include discharge and analysis results of wastewater treatment (effluent) from the WWTP area at the campus, wastewater treatment processes, content in the water treatment process (influent wastewater), chemicals used in wastewater treatment processes, production waste, and energy consumption. The dependent variables consist of potential environmental impacts resulting from the research, including carcinogenicity, respiratory inorganics, ionizing radiation, ozone layer depletion, non-carcinogens, respiratory organics, ecotoxicity, terrestrial ecotoxicity, aquatic acidification, aquatic eutrophication, terrestrial acid/nutrient enrichment, land occupation, global warming, non-renewable energy, and mineral extraction. The scope of analysis is depicted in Figure 1.

Secondary data collected are analyzed using the LCA method with the assistance of Simapro 9.1.0.11 software. While most published LCA studies on WWTPs follow the attributional modeling approach, the use of consequential modeling is increasingly applied, especially when system changes significantly impact the area of interest, such as implementing new process technologies or changing the sludge treatment process [19].

Goal and scope definition

Before initiating the LCA, the objectives and scope are defined to elucidate the relationship between the product system, functional units, and system boundaries. The primary goal is to identify the environmental impact of domestic wastewater treatment at the WWTP. The LCA scope includes the production of wastewater and production waste.

Life cycle inventory

This stage involves collecting data on potential emissions, consumption of raw materials, energy, and waste in the production process at the WWTP. The emission factors are based on the IPCC [20] standards for wastewater treatment, namely 0.25 kg CH_4/kg COD and 0.48 kg CH_4/

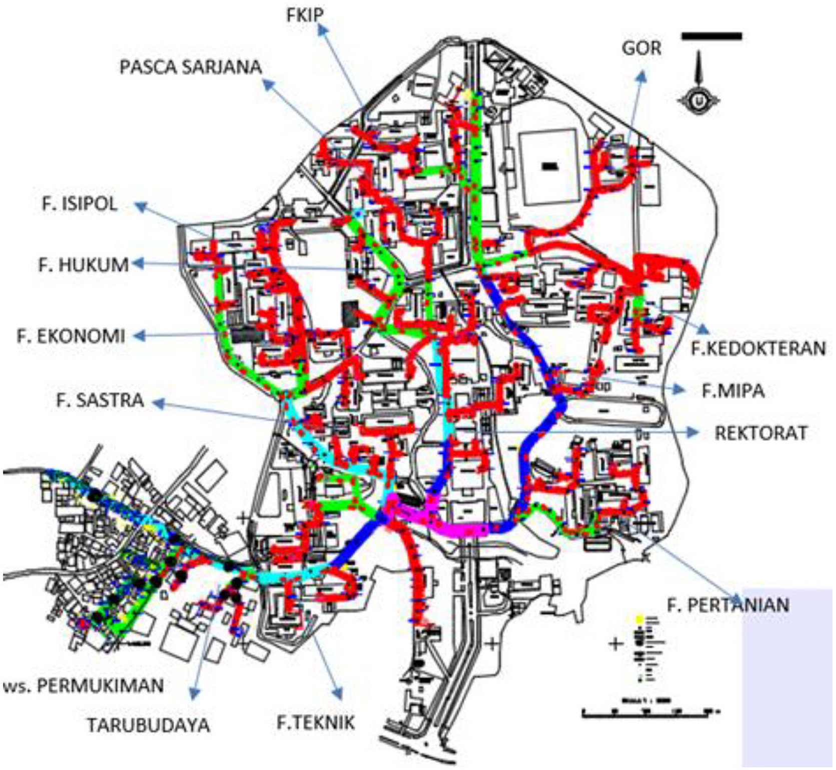


Fig 1. Analyzed scope: waste water network service WWTP in Surakarta

kg BOD [21]. This calculation method does not account for environmental conditions in the processing unit, necessitating direct field measurements. Emission calculation follows (Eq. 1):

$$\textit{Emission load}\ (E) = \textit{Emission factor}\ (EF) \times \textit{Activity data}\ (\text{amount of materials that produce emission}) \quad (1)$$

Life cycle impact assessment

The life cycle impact assessment (LCIA) of our study scrutinizes the environmental impacts associated with the wastewater treatment process. In our study's life cycle impact assessment, we analyze the environmental impacts of a wastewater treatment process. The LCIA proceeds through several distinct stages:

- Characterization: here, we employ the Eco-Indicator 99 method, which breaks down environmental impacts into 11 detailed categories (Fig. 6). These categories then roll up into three broader groups that reflect the overarching damage: human health, ecosystem quality, and resource depletion. This step quantifies the direct impact of emissions and resource use on these areas.
- Centrum voor Milieukunde Leiden (CML) method: concurrently, we use the CML method, which operates at the midpoint level. This means it evaluates environmental impacts at an earlier stage in the impact pathway, focusing on the direct effects on the environment, such as eutrophication or ionizing radiation. It's a detailed method that looks at a variety of categories to assess the immediate environmental impacts.
- Normalization and weighting: using the Eco-Indicator 99 method within SimaPro software, we calculate the potential impacts from our inventory data (Fig. 7). This step adjusts the results to a common scale (normalization) and assigns importance to the different categories (weighting).
- Single score calculation: finally, we synthesize all the data into a single score that reflects the total environmental damage. This score is designed to help stakeholders easily understand the overall impact and prioritize actions based on these results.

By integrating the midpoint focus of the CML method with the endpoint aggregation of Eco-Indicator 99, we ensure a thorough and layered analysis. This approach allows us to benefit from the detailed, category-specific insights provided by CML while also leveraging the broader, comprehensive environmental damage assessment offered by Eco-Indicator 99. The dual methodology employed in our LCIA adheres to best practices, enabling a nuanced understanding of environmental impacts and supporting well-informed decisions for improving wastewater treatment sustainability.

Interpretation

This stage is crucial as it correlates the findings with the initial goals and the scope of the study. Data from the inventory, which captures the energy and material flows of the wastewater treatment process, is synthesized with the impact assessment outcomes. This synthesis focuses on understanding the environmental impact categories like resource depletion, human health, and ecosystem quality. Key areas, or 'hotspots', within the treatment process that significantly affect the environment are identified, pinpointing where improvements can have the most substantial effect. Potential improvements are evaluated for their environmental benefits, aligning these with practical considerations for enhancing the treatment process's sustainability. Our findings are validated by comparing them with existing literature and industry benchmarks, ensuring the integrity and reliability of our conclusions. An uncertainty analysis is conducted to address any assumptions or variability in the data, which ensures the confidence in our conclusions. Ultimately, the study culminates in drawing well-informed conclusions about the environmental performance of the wastewater treatment operation

Table 1. Emission factors for electricity consumptions, BOD, and COD

Parameter	Emission factors	Sources
Electricity consumptions	0.725 $kgCO_2/kWh$	[22]
BOD	0.48 kg CH_4/kg BOD	[20]
COD	0.25 $kgCH_4$/kg COD	[23]

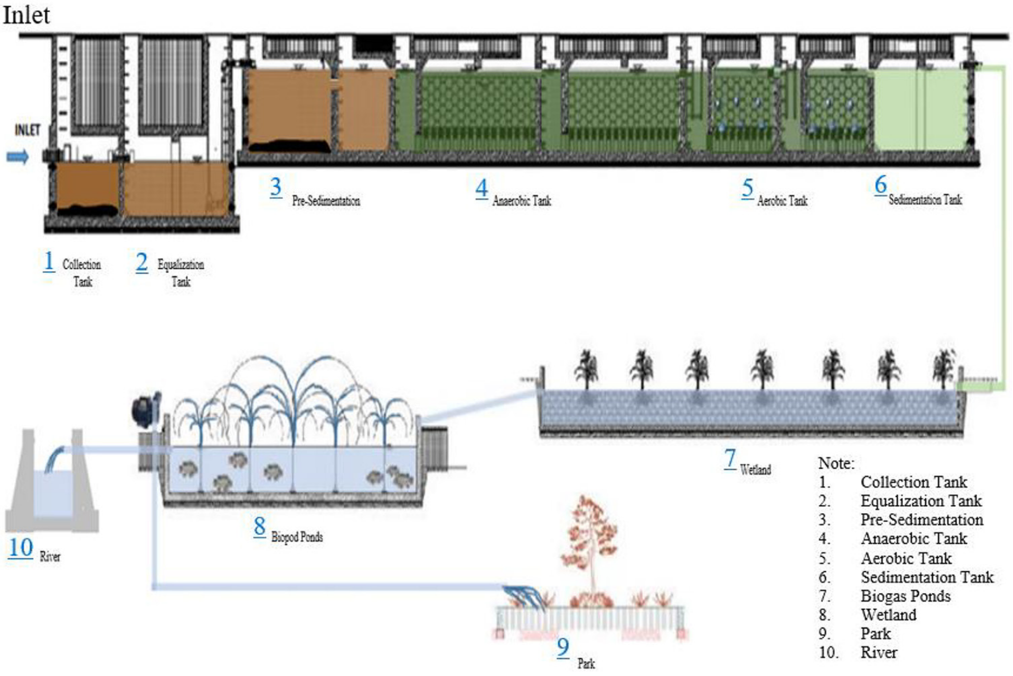
and provides clear recommendations for reducing its impact. These conclusions and recommendations are then translated into a coherent narrative, structured to effectively communicate the key findings to stakeholders, thus facilitating the implementation of sustainable practices in wastewater treatment operations.

RESULTS AND DISCUSSION

The data processed using SimaPro software yielded results categorized into four types of assessments: network, characterization impact assessment, normalization impact assessment, and single score. Utilizing the Eco-indicator 99, the study identified 11 impact categories. These categories are evaluated based on a weighted structural hierarchy, grouped under three damage categories: human health, ecosystem quality, and resources. These areas are significant as they have historically discharged domestic liquid waste into waterways leading to a lake. Figure 2 illustrates the operational WWTP in the area, while Figure 3 presents a wastewater treatment process flow chart.

Sources of wastewater in this study include campus community students, lecturers, staff, and residents from nearby villages. The average water usage per person (students, lecturers, and staff) is estimated at 30 liters/day, resulting in a total

Fig. 2. Wastewater treatment plant (WWTP) existing condition in Surakarta



Note:
1. Collection Tank
2. Equalization Tank
3. Pre-Sedimentation
4. Anaerobic Tank
5. Aerobic Tank
6. Sedimentation Tank
7. Biogas Ponds
8. Wetland
9. Park
10. River

Fig. 3. Wastewater treatment plan flow chart

Table 2. Wastewater quality in Universitas Sebelas Maret, Surakarta

No	Parameter	Unit	Results
1	BOD 5 days 20°C	mg/L	30
2	COD	mg/L	20
3	Total suspended solid (TSS)	mg/L	36
4	Oil & grease	mg/L	1.47
5	Ammonia (NH_3-N)	mg/L	9
6	pH	-	7.04
7	Total phosphate (PO_4)	mg/L	1.2
8	Surfactants anionic MBAS	mg/L	0.08
9	Nitrogen total	mg/L	10

wastewater discharge of 1,293.6 m³/day. The research observed an increase in discharge around noon. According to Table 2, all tested wastewater parameters are below the quality standard set by the Minister of Environment Regulation No. 68 of 2016 [24]. These parameters encompass organic and nitrogen content, total phosphate, and surfactants. However, it's noted that the total coliform parameter, an essential indicator of wastewater quality, has not been measured. Total coliforms, predominantly originating from black water and greywater, are critical for determining compliance with quality standards. Figure 4 demonstrates the inventory data entered into the software, providing insights into the performance of the wastewater treatment plant. When related to the input and output wastewater discharge, this data reflects the overall pollution load generated by the facility.

These parameters include organic and nitrogen parameters and total phosphate and surfactants. There is a total coliform parameter that has not been measured, which is an important parameter that forms the basis for whether the wastewater is following the quality standard or not. Wastewater contains a lot of total coliforms produced from black water and greywater. Figure 4 shows the inventory data entered into the software to see the performance of the wastewater treatment plant. When associated with the discharge of input and output wastewater, it results in a pollution load.

In the life cycle inventory stage of our study (Table 3), we've meticulously gathered data on the raw materials, energy, and emissions involved in the wastewater treatment process at Sebelas Maret University. We've set up a mass balance to track the material and energy flows, which is vital

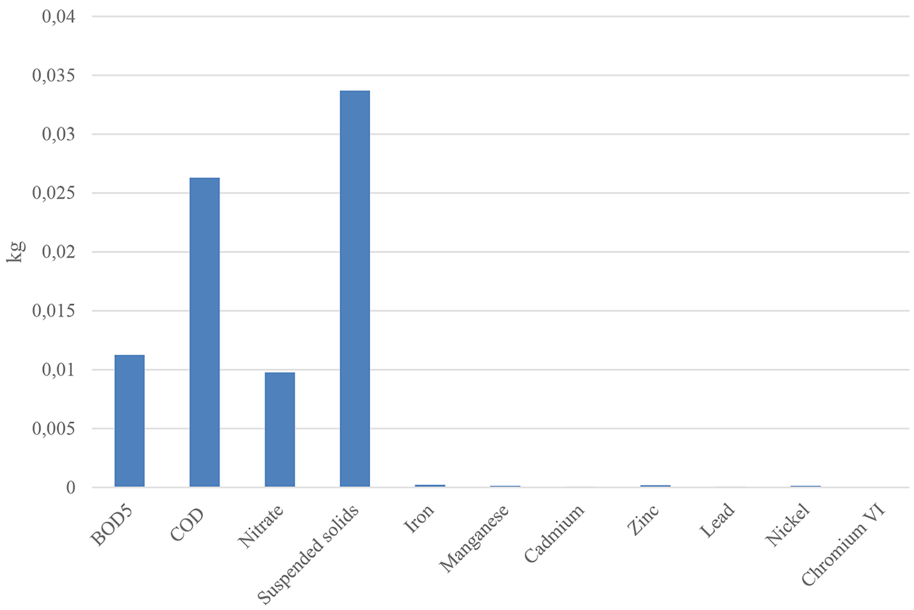


Fig. 4. Inventory data WWTP in Surakarta

Table 3. Inputs and monitoring parameters for life cycle inventory of wastewater treatment process

Category	Description
Raw materials	Water inflow rate: 10 liters/second
Energy consumption	Daily electricity usage: 18.4 kWh
Pollutant loads	Total suspended solids (TSS), biological oxygen demand (BOD), chemical oxygen demand (COD), nitrogen (N), phosphorus (P)
Chemical usage	None (treatment units do not use chemicals in processing)
Waste generation	Office paper waste: approximately 1 kg/month
Monitoring parameters	Organic components, nitrogenous compounds, total phosphate, surfactants

for ensuring accuracy in our assessment. We've detailed the specific load of pollutants processed, including total suspended solids, biological oxygen demand, chemical oxygen demand, nitrogen, and phosphorus. The flow rate of the wastewater entering the treatment is measured at a steady 10 liters per second, while the daily electricity use for the entire wastewater treatment plant operations totals 18.4 kWh. Notably, our study's treatment units do not use chemicals to treat the wastewater. In terms of waste generation, the associated office produces roughly 1 kg of paper waste each month. For monitoring purposes, we concentrate on various key components such as organic matter, nitrogenous substances, total phosphate, and surfactants, which are indicative of the treatment's efficacy. However, our current inventory does not include measurements for total coliform counts, which are a critical standard for assessing the quality of treated wastewater. Since coliforms are typically found in both black and grey water, their presence is crucial for evaluating whether the treatment meets the necessary quality benchmarks. This comprehensive data collection in our LCI aims to offer clarity and facilitate the reproduction of our environmental impact analysis of the wastewater treatment process.

Following the LCI, the LCIA stage commences, which assesses the environmental impacts based on the collected inventory data. The CML-IA (Centre of Environmental Science of Leiden University Impact Assessment) method is employed for this impact assessment. This stage involves comparing the LCI results against various environmental impact categories. An environmental impact network diagram is constructed to visualize the connections between different processes and their potential environmental impacts. In this network, upward arrows indicate the wastewater production process, red lines represent processes contributing to environmental impacts,

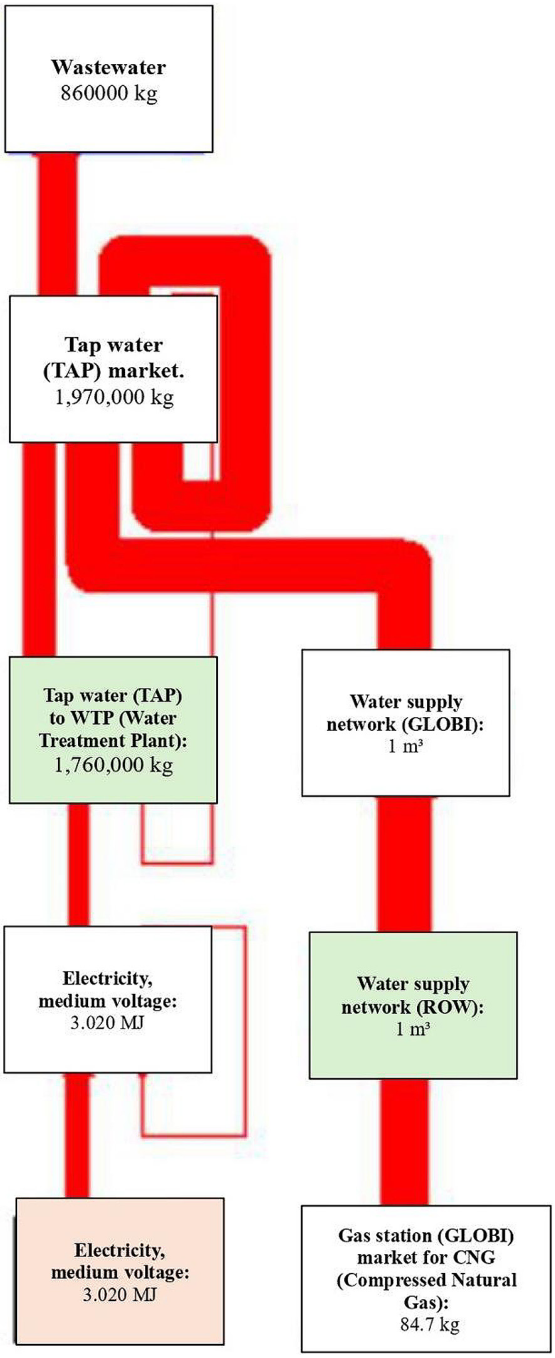


Fig. 5. Network result characterization with SimaPro 9.1.0.11

and green lines signify emissions that are treated to mitigate their harmful effects, particularly on human health. The thickness of the red lines in the diagram correlates to the magnitude of each process's impact on the environment. The most substantial environmental impact, depicted by the thickest red line, is associated with using natural gas or electrical energy, largely due to the extensive use of pumps for transferring raw water and elevating wastewater to the treatment units. After establishing the network (as seen in Figure 5), the subsequent step is data processing to quantify the environmental impacts of material and energy use. For instance, the impact of respiratory inorganics is traced back through various treatment units: the collecting tank, equalization tank, presettling basin, anaerobic unit, aerobic unit, final settling basin, and biopond. The network results indicate the largest contributors to the impact of respiratory inorganics, providing a clearer understanding of which processes require optimization to reduce environmental burdens.

The diagram illustrates a significant environmental load from wastewater treatment, indicated by a prominent red line. Tap water inputs are shown as two distinct streams contributing to the environmental impact, which may reflect different stages or sectors within the water system that are being assessed. The diagram also details electricity usage, with two entries for medium voltage consumption, highlighting the WWTP's dependency on electrical energy and its substantial contribution to the environmental impact. Furthermore, the diagram includes a contribution from gas emissions, likely related to using natural gas within the WWTP, perhaps for heating or power generation. Two parts of the diagram note water supply network impacts, suggesting multiple points of interaction or varying processes within the WWTP that necessitate water input.

The thickest red lines in the network result underscore the considerable impact of energy use, mainly due to the extensive application of pumps needed to transfer raw water and elevate wastewater to treatment units. These lines indicate the most impactful processes, with energy-intensive operations marked as key areas for potential improvement. Overall, the analysis of Figure 5 indicates that both wastewater and energy usage are critical focal points for reducing the respiratory inorganic impacts associated with the WWTP operations. Optimizing these aspects could lead to enhanced environmental performance of the wastewater treatment process.

The analysis conducted using SimaPro 9.1.0.11 software revealed that various emissions contribute to the impact of respiratory inorganics. Substances such as benzene, hydrocarbons, methane, and xylene are among the pollutants that lead to respiratory inorganics. A significant factor contributing to ofinhaling inorganic substances' inhalation is the extensive use of electricity. In Indonesia, electricity generation primarily relies on coal combustion, which emits substantial quantities of dust and other pollutants. The inhalation of these inorganic particles is recognized as having a detrimental environmental impact on human health, specifically affecting the respiratory system.

Transforming raw water into clean water has been identified as the largest source of emissions in this context, surpassing the electricity used in wastewater treatment units. Additionally, emissions from paper waste contribute to the overall environmental impact, albeit to a lesser extent. The study employs the Eco-indicator 99 methodology, categorizing environmental impact into 11 different types. According to the Eco-indicator 99 framework, these environmental impacts are further classified into three main groups, detailed in Table 4 of the study. This classification helps in understanding how these impacts can affect both human health and the broader ecosystem.

Figure 6 illustrates the impact assessment across different environmental categories for two distinct inputs: wastewater and other utilities. Each category is evaluated based on its contribution to the overall environmental impact, presented on a scale from 50% to 100%. Notably, the bar graph shows fossil fuels have the highest impact, followed by minerals and land use. The respiratory inorganics and respiratory organics, on the other hand, have relatively lower impacts. However, the current text does not appear to correspond directly with the results in Figure 6, as it should reflect the proportionate contributions of wastewater and other utilities to each environmental category.. The treatment process itself is shown to be responsible for environmental impacts across all assessed categories. Energy use in wastewater treatment also emerges as a significant contributor, outpacing the impacts of wastewater quality and paper waste produced by the facility. This chart indicates that the system's primary driver of global warming is the emission of greenhouse gases such as CO_2, CH_4, and N_2O during

Table 4. Description of environmental impact based on Eco-indicator 99

No	Environmental impact assesment category	Impacts
1	Losses to human health	Carcinogens
		Respiratory organics
		Respiratory inorganics
		Climate change
		Radiation
		Ozone layer
2	Ecosystem quality	Ecotoxity
		Acidification,
		Land use.
3	Resource	Minerals
		Fossil fuels

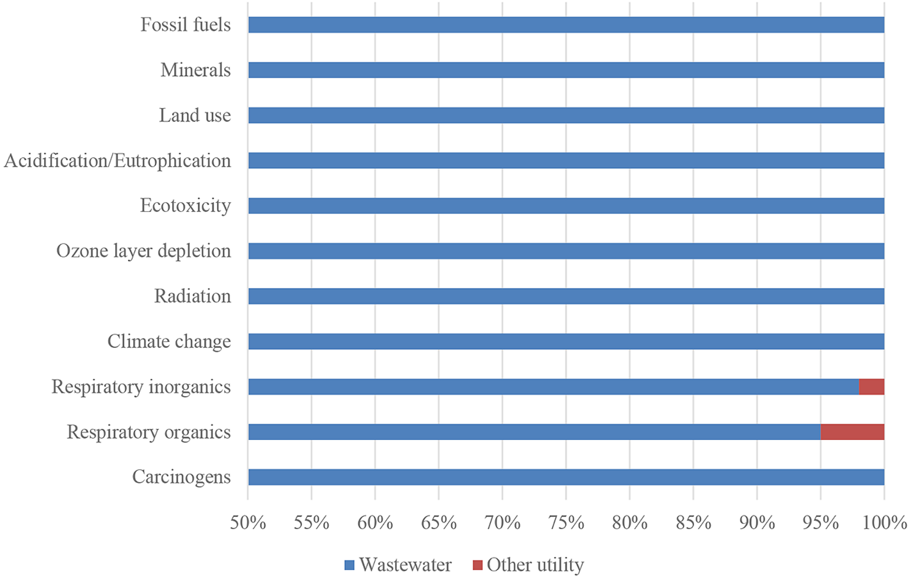


Fig. 6. Impact assessment of wastewater treatment compared to other utilities using the cumulative impact assessment method

the treatment process, with CO_2 emissions from the WWTP's energy use also recognized as a key contributor to climate change [25]. Moreover, the graph touches on the issue of non-renewable energy sources, including coal, gas, petroleum, uranium, and natural gas, highlighting their usage rates faster than natural regenerative processes [26, 27]. This implies a substantial environmental footprint in immediate emissions and the depletion of non-renewable resources, emphasizing the need for sustainable management of these energy sources in the context of wastewater treatment operations.

The impact characterization revealed that ecotoxicity registers the highest environmental impact losses. This outcome is attributed to the likelihood that the surface raw water (rivers) awaiting treatment into wastewater contains a significant concentration of inorganic and organic compounds. Conversely, the ozone layer is the least impacted category, which aligns with the absence of ozone-depleting chemicals in water production. Land use is also highlighted as a major impact factor, driven by the spatial demands of establishing and operating a drinking water treatment plant to convert raw water into tap water. When analyzing human health impacts, the Disability-Adjusted Life Years (DALY) metric is utilized, which accounts for the years of life lost due to disability or premature death. The DALY scale, employed by organizations such as the WHO and the World Bank, is notable for its ability to incorporate changes in carcinogenic risk due to environmental alterations.

Furthermore, the unit PDF*m^{2}yr, or potentially disappeared fraction of species per square meter per year, measures the potential loss of species diversity attributable to the environmental impact process on ecosystem quality. The PDF value is calculated based on the relative differences in species count between reference conditions and those altered by human activity [28]. The impact characterization figures are divided by a normalization reference value during the normalization stage. The normalization results show that the three categories of environmental impact losses, in descending order of magnitude, are impacts on human health, resource depletion, and ecosystem quality. This ordering underscores the broader implications of water treatment processes, emphasizing the need for comprehensive environmental management strategies that take into account a wide spectrum of potential impacts.

The analysis within the study incorporates a single-score normalization using SimaPro software, depicted in Figure 7 as a pie chart. This chart contextualizes the environmental impacts across various categories, translating them into a percentage format that delineates their relative significance. In this visualization, the impact of fossil fuels is the most substantial, constituting 61% of the environmental burden. This is significant and underscores the heavy reliance on non-renewable energy sources within the wastewater treatment process. Following fossil fuels, respiratory inorganics account for 23% of the impact. This substantial figure highlights the concern for air quality and the potential human health effects associated with releasing inorganic compounds during treatment operations. Respiratory organics are also notable, comprising 9% of the total impact, which points to the release of volatile organic compounds and other organics that can affect respiratory health. Other impact categories such as climate change, carcinogens, and others occupy smaller portions of the pie chart, each contributing to the overall environmental impact but to a lesser degree when compared to the categories mentioned above. The presence of climate change as a category, even at 4%, is a critical indicator of the greenhouse gas emissions associated with the treatment processes.

The pie chart is an effective tool for quickly communicating the distribution of environmental impacts and can guide decision-makers in prioritizing areas for improvement. For instance, the dominance of fossil fuels suggests that strategies for energy optimization and transition to renewable sources could have a marked effect on reducing the overall environmental footprint of the WWTP. Normalization to a single score aids in simplifying complex LCA results, enabling

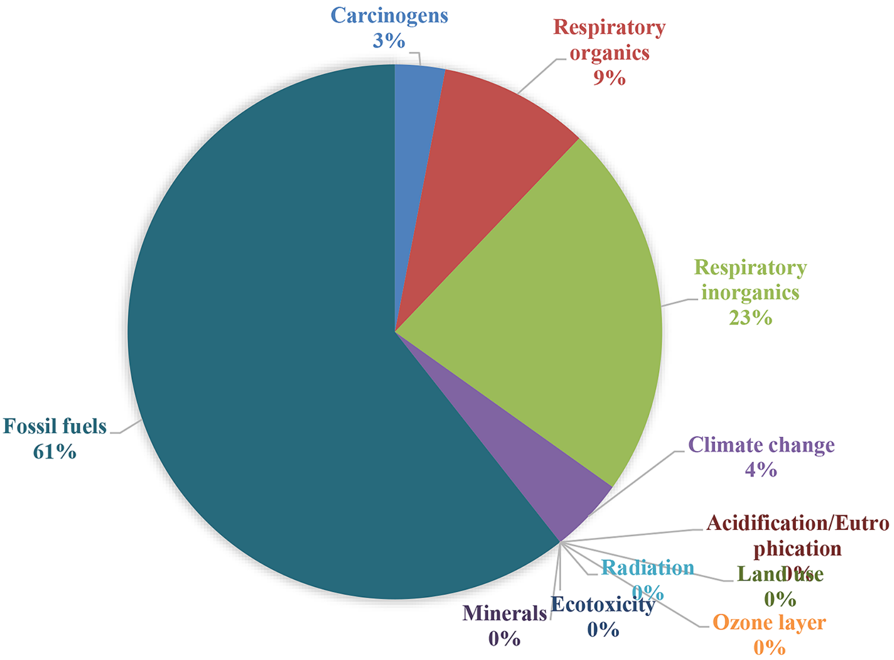


Fig. 7. Normalization of impact categories using the Eco-Indicator 99 (EI99) method as calculated from SimaPro data

stakeholders to ascertain which environmental concerns warrant immediate attention and action.

LCA adopts a comprehensive perspective, encompassing both indirect and direct impacts of WWTP on a specified array of environmental indicators. To streamline decision-making, it may be beneficial to narrow down the scope of indicators for impact assessment [29]. For wastewater systems in particular, eutrophication, climate change, and ecotoxicity are the principal indicators. These recommended metrics align with those proposed for national wastewater systems in the United Stated [30] and have the potential to link with existing wastewater monitoring practices, such as nutrient waste concentration and dynamic modeling efforts [31]. Additionally, scenario analysis is a tool to test the robustness of assumptions and general conclusions. By applying alternative electricity mixes, for instance, one can gauge whether conclusions hold steady across different geographic locations and their respective energy infrastructures [32]. This approach allows for a more tailored and locally relevant environmental impact assessment.

Comparing our study to others in the field, we find a range of approaches to assessing the environmental impact of waste management and energy production from waste. In China, the production of biogas from food waste in university campuses, such as in the case of Huazhong University of Science and Technology, has been analyzed for its life cycle environmental impact, focusing on climate change, acidification, eutrophication, and photochemical oxidation [33]. This approach aligns with our emphasis on assessing impacts like climate change and eutrophication, although we do not specifically address biogas production from food waste [33]. Studies comparing membrane bioreactor (MBR) systems to conventional activated sludge units in municipal wastewater treatment, focusing on factors like acidification potential and global warming potential, offer a similar methodological framework to ours, particularly in our focus on emissions and energy use [34]. Their findings on the environmental superiority of MBR systems provide an interesting comparison point for the effectiveness of different treatment technologies [34]. The broader examination of LCA in wastewater treatment technology offers a wide-angle view of the field, emphasizing the importance of LCA in understanding the environmental impacts of various treatment methods [35]. This perspective mirrors our own recognition of LCA as a comprehensive tool for environmental impact assessment. The assessment of Clemson University's carbon footprint using a life cycle assessment approach touches on sources such as steam generation, transportation, and wastewater treatment, which is comparable to our approach in terms of scope. Their results, particularly in the context of greenhouse gas emissions, can be a benchmark for our study's findings [36]. Finally, the assessment of environmental impacts of large centralized wastewater treatment plants in different seasons provides insight into the seasonal variability of treatment performance and its environmental impacts [37]. While our study does not differentiate between wet and dry seasons, this aspect offers a valuable dimension for future research considerations, especially in the context of rainfall and influent flow rates.

The study's findings regarding the minimal impact on the ozone layer are particularly revealing. The negligible percentage of ozone layer depletion, as indicated in the environmental impact assessment, correlates directly with the absence of ozone-depleting chemicals in the wastewater treatment processes at the academic institution. This outcome is encouraging, as it suggests adherence to environmental regulations that restrict the use of substances known to harm the ozone layer and reflects a conscious effort to minimize harmful emissions in the institution's operations. A striking 97.7% of the acidification potential within the environmental profile is sourced from all construction phases, with the remainder attributable to emissions from transportation [38]. The plastic production process is highlighted as a contributor to greenhouse gas emissions, involving electrical energy, heat, combustion, and chemical use in production [39].

The pronounced 61% impact of the WWTP operations on fossil fuels is indicative of the energy-intensive nature of wastewater management processes. This considerable figure points to the reliance on energy sources for running the facility's equipment such as pumps, aeration systems, and other machinery necessary for treating wastewater effectively [40, 41]. This reliance on fossil fuels for energy translates to higher carbon emissions [42, 43, 44], considering that burning these fuels is one of the largest sources of greenhouse gas emissions globally [45]. Therefore, the WWTP's significant energy demands contribute to the broader environmental issue of climate change, underscoring the need for a transition towards more sustainable energy sources within such utilities. The high impact of fossil fuels also brings attention to potential areas for improvement in plant operations. The energy efficiency of the WWTP could be enhanced by upgrading to more modern, energy-saving technologies or redesigning certain processes to reduce energy consumption [46]. Incorporating renewable energy sources such as solar or wind power could significantly reduce the dependency on fossil fuels [47], aligning the WWTP's operations with sustainable practices that are becoming increasingly crucial in the face of climate change. Furthermore, the impact assessment underscores the importance of evaluating the full life cycle of wastewater treatment operations to identify all significant environmental impacts. While direct emissions during the operational phase are often the focus, the construction phase, including the manufacturing and transporting materials such as plastics and metals, also plays a crucial role in the overall environmental profile of such facilities.

The findings of the LCA of the WWTP at Sebelas Maret University in Surakarta, Indonesia, present important considerations for policymakers concerned with environmental management within academic institutions. The high energy consumption identified in the treatment facility, largely due to electricity and natural gas use, highlights the need for an urgent shift toward renewable energy sources within these systems. The extensive environmental footprint revealed by the LCA points to the necessity of integrating sustainable practices into the core operational framework of wastewater treatment facilities. Policies could be introduced that incentivize the adoption of renewable energy technologies, such as solar or wind power, specifically tailored to meet the energy demands of treatment plants. Furthermore, capturing and utilizing methane from anaerobic digestion mitigates greenhouse gas emissions and can generate a valuable energy resource [48, 49], thereby reducing reliance on non-renewable sources.

The LCA's impact characterization underscores the need for improved wastewater treatment technologies that lessen ecotoxicity. Implementing advanced filtration and bioremediation systems could reduce the presence of harmful inorganic and organic compounds, thus diminishing the ecotoxic impact on local ecosystems and human health [50, 51]. Policymakers should consider supporting research and development efforts to improve treatment efficiencies while minimizing ecological disruption. Additionally, the normalization of environmental impacts demonstrated by the SimaPro analysis is a key indicator of where policy interventions could be most effective. For instance, the high contribution of respiratory inorganics to human health impacts should direct attention to reducing emissions from the energy sector, particularly those associated with coal and fossil fuel combustion. Policies promoting energy efficiency, air quality standards, and emission reductions could directly address these concerns.

CONCLUSIONS

The LCA of the wastewater treatment process in Surakarta has provided comprehensive results, including a network diagram, characterization impact assessment, normalization impact assessment, and a single score that encapsulates the overall environmental impact. The LCA has identified that the most significant environmental impacts stem from the emissions associated with transforming raw water into clean water and using natural gas or electrical energy. In terms of specific environmental categories, electricity use has been pinpointed as a critical factor that indirectly impacts the depletion of natural resources, particularly fossil fuels, and contributes to health-related impacts due to climate change. This is primarily attributed to the combustion of CO_2. The substantial consumption of electricity or energy within the treatment process is primarily linked to the operation of high-power pumps necessary for sourcing raw water and transporting this water over extended distances to the water treatment plant.

The category of respiratory inorganics is most affected by the energy extraction processes, particularly coal and fossil fuels, which lead to the emission of greenhouse gases, including ammonia, nitrogen monoxide, nitrogen oxides, particulates smaller than 2.5 micrometers, sulfur dioxide, and sulfur trioxide. Global warming impacts are traced back to using electrical energy and the emissions of greenhouse gases such as CO_2, CH_4, and N_2O. Additionally, the consumption of electrical energy has been shown to affect the availability of non-renewable energy resources like gas, oil, and uranium found within the earth. This highlights the need for energy conservation and the exploration of more sustainable energy sources. To mitigate the environmental impacts identified through the LCA, potential improvement initiatives for the Surakarta region could include a thorough environmental impact analysis on the water treatment plant operations, the utilization of methane through anaerobic digestion processes, and the development of green spaces. Such strategies could reduce environmental impacts and contribute to more sustainable wastewater management practices in the region.

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