Jurnal Presipitasi
Media Komunikasi dan Pengembangan Teknik Lingkungan
e-ISSN: 2550-0023

Vol 22, No 2, 2025, 528-546
Article available at [homepage presipitasi]

Regional Case Study

Life Cycle Assessment of the Campus Wastewater Treatment Using Lab-scale Anaerobic Baffled Reactor

Hafif Ahmad Abdul Aziz[1], Anie Yulistyorini[2*], Ridwan Muhamad Rifai[2], Sofiah Hamzah[3]

[1] Civil Engineering Study Program, Department of Civil Engineering and Planning, Faculty of Engineering, Universitas Negeri Malang, Semarang St. No. 5, Malang 65145, Indonesia

[2] Environmental Engineering Study Program, Department of Civil Engineering and Planning, Faculty of Engineering, Universitas Negeri Malang, Semarang St. No. 5, Malang 65145, Indonesia

[3] Environmental Sustainable Material Research Interest Group, Faculty of Ocean Engineering, Technology, and Informatics, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia

* Corresponding Author, email: anie.yulistyorini.ft@um.ac.id

Abstract

In Indonesia, the waste sector is responsible for 10.59% (130,188.21 GgCO2e) of global warming emissions, one of which is from campus domestic wastewater due to the lack of wastewater treatment plants. Only 0.2% of the 6,472 campuses have treatment systems. For example, Universitas Negeri Malang (UM) uses a fabricated anaerobic baffled reactor (FABR) for wastewater treatment plants as part of its green campus initiatives; however, it is available only for several buildings and does not treat all wastewater generated from campus activity. However, the Life Cycle Assessment (LCA) of ABR systems has not been widely studied, especially when used to treat campus wastewater. This study aimed to conduct the LCA of the laboratory-scale ABR system in campus wastewater treatment with a gate-to-gate scope using Simapro 9.1.11 and the CML-IA Baseline. Three scenarios were tested: untreated wastewater, ABR equipped with peristaltic pumps, and ABR without pumps. The results indicated that ABR treatment had a significantly lower environmental impact than untreated wastewater, with the greatest reduction in global warming potential (1.51E-08 to 4.98E-11), followed by reductions in eutrophication and photochemical oxidation. This study was limited to the ABR system; future research could be expanded to include the full lifecycle, from material collection to the final results.

Keywords: Life cycle assessment; anaerobic baffled reactor; campus wastewater treatment; environmental performance; sustainable campus

1. Introduction

Global warming is currently the main focus of environmental problems. This international problem is caused by the high influence of greenhouse gases (GHG) from various human activities (Irianto, 2024). The International Panel on Climate Change (IPCC) reported in 2024 that the earth's temperature is increasing every year by 1.5 to 2 degrees, with a contribution from GHG in Indonesia of 10% or 2.3% of the global GHG effect (Martin et al., 2023). The national climate describes 40.6 billion tons of GHG produced in Indonesia, which contributes to global emissions (IPCC, 2023). The GHG effect is a group of gases in the atmosphere, and is composed of several gases, such as nitrogen oxide (N_2O), carbon dioxide (CO_2), methane (CH_4), ammonium (NH4), chlorofluorocarbons (CFCs), and other gases (BMKG, 2022). The increase in GHG emissions is triggered by the processing and disposal of waste and wastewater from human activities.

The presence of untreated wastewater can decrease environmental quality. Globally, the waste sector ranks fourth at 3.2%, in which Indonesia contributes to global warming effects of 10.59% or 130,188.21 Gg CO2e of national emissions in 2023 (KLHK, 2024). These waste sources can originate from domestic and industrial wastewater, as well as solid waste (UNCRD, 2020). Wastewater can contribute to CH4 as a result of GHG emissions, which play a role 28 times greater than the potential of CO2 (Mustikaningrum et al., 2021). Domestic and industrial wastewater contains other substances, such as BOD, *E. coli*, NH_4, N_2O, and COD, which contribute to climate change and global warming (Nasrullah and Rahmayanti, 2024). These pollutants are also generated from campus wastewater.

Most campuses do not have centralized wastewater treatment for greywater and blackwater. The most common type of blackwater is treated in septic tanks, but greywater is discharged into the environment without any further treatment. According to the Higher Education Database Center in Indonesia, only 0.2% of the 6,472 universities have campus wastewater treatment plants (CWWTPs) for further treatment (PDDikti, 2024). To reduce GHG emissions, several campuses already have CWWTPs, such as ITB, UNS, ITS, and UM (Isnanto, 2024). UM, as a campus committed to realizing a green and sustainable campus through domestic waste treatment, continues to make efforts to reduce the increasing rate of GHG.

Domestic wastewater on campus generally comes from greywater and blackwater discharges from toilets, bathrooms, sinks, and kitchens (Idrus et al., 2024). Currently, UM occupies an area of approximately 463,992 m^2 with 10 faculties. The university provides four low-cost wastewater treatments using FABR's (UM Green Campus, 2022). ABR can be considered a wastewater treatment technology consisting of compartments and upright baffles, where airflow can move up and down through several compartments, accompanied by the remaining sludge and microorganisms in the anaerobic process (Mapanget et al., 2024). Previous ABR research at the laboratory scale has shown that this system removed 28% of turbidity, 22% of total dissolved solids (TDS), and 54% of total coliform (TC), with an effluent concentration of approximately 153 MPN/100 ml (Yulistyorini, 2021).

The FABR supports the green building principles issued by the Green Building Council Indonesia (GBCI) regarding Building Environment Management (BEM) (GBCI, 2013). The application of a WWTPs facility on the UM campus may help mitigate the effects of climate change (Hu et al., 2024). However, the application of ABR as a campus WWTP needs to be monitored and analyzed for effluent quality and environmental impact, which contributes to global warming.

The environmental impact analysis of the campus wastewater treatment system using FABR at UM has not received sufficient attention. Impact analysis is important because the anaerobic process in the system produces emissions and affects the environmental burden. To conduct this analysis, the LCA approach that refers to SNI ISO 14040: 2016 and 14044: 2017 (KLHK, 2021) is important to implement. Previous studies (Lei et al., 2024; Yan et al., 2023; Samuchiwal et al. 2023) have demonstrated the use of LCA to assess the environmental impact of ABR technology. Based on these studies, ABR systems can produce GHG emissions of approximately 0.015 CO2-eq/m^3, which is estimated to be 85% lower than conventional active sewage treatment processes (Lei et al., 2024). Other studies have also shown that anaerobic wastewater treatment tends to have a relatively lower environmental impact than conventional activated sludge systems, especially in terms of its nutrient and energy recovery potential, as well as its ability to capture dissolved methane from effluent (Yan et al., 2023). According to Samuchiwal et al., (2023), the results showed that compared to conventional activated sludge-based treatment processes, sequential microbial-based anaerobic reactor technology can give around 41.5% lower environmental impacts, including a 46.15% decrease in negative impacts on human wellness and a 42.85% decrease in negative impacts on environmental quality. However, despite the variety of design approaches and methods used, the comparison of life cycle studies between anaerobic technologies and other treatments is limited. Therefore, LCA practitioners and wastewater-related research need to further investigate the various treatments of the ABR systems (Yilmaz et al., 2024). This study investigated the environmental impact of untreated and treated campus wastewater on a laboratory scale using LCA. This study offers recommendations to reduce these impacts using Simapro 9.1.11 and is expected to improve the performance of wastewater management on campus.

2. Methods

This research was conducted at the UM campus, where wastewater samples were collected from the UM Rectorate Building. The data in this study were generated from laboratory analyses of untreated and treated wastewater. The use of electricity, mainly for pumping, was also monitored (e.g., kWh). The parameters analyzed in this experiment were CH4, NH4, NO3, PO4, NO2, DO, and COD.

Simapro 9.1.11 was used according to the principles of SNI ISO 14040: 2016 and 14044: 2017 on the framework, principles, and guidelines for LCA (Zhu et al., 2024). LCA comprises four stages in LCA, including determining the purpose, goal, and scope; the life cycle inventory data (LCI) stage; the life cycle impact assessment (LCIA) stage; and finally, concluding the results of data analysis or interpretation. The flow and stages of LCA are shown in Figure 1.

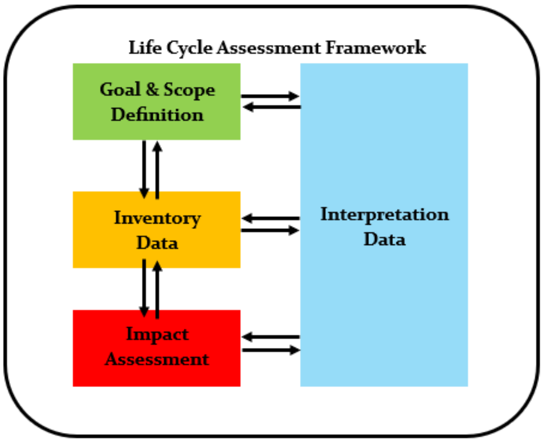

Figure 1. Flow and stage of LCA framework

The first stage of Figure 1 is to determine the goal and scope that will be studied in the LCA of ABR. The goal and scope were determined to identify the objectives and limitations that need to be analyzed (Jang et al., 2024). This study aimed to investigate the environmental impact of campus wastewater through laboratory-scale ABR experiments and assessment of untreated wastewater (inlet). The scope that will be studied from this research is to use gate-to-gate. The gate-to-gate scope was chosen because this LCA analysis focuses only on each processing system unit, as shown in Figure 2.

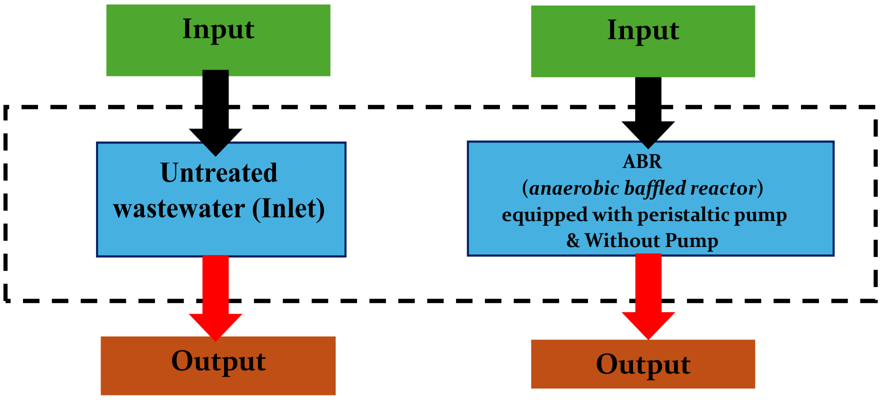

Figure 2. The scope of LCA

The second stage of the LCA is the data inventory, which is studied by collecting input, product, and output data from the system to be analyzed in the LCA (Ferdous et al., 2024). In this study, the data inventory generated from the Simapro 9.1.11 database, treated wastewater analysis results, untreated wastewater (inlet) characterization, and the amount of electricity used for pumping (for example, KwH). The input of this system was divided into three different types: untreated wastewater (inlet), ABR equipped with a peristaltic pump, and ABR without pumps. The data was obtained from a three-month laboratory-scale experiment (Figure 3).

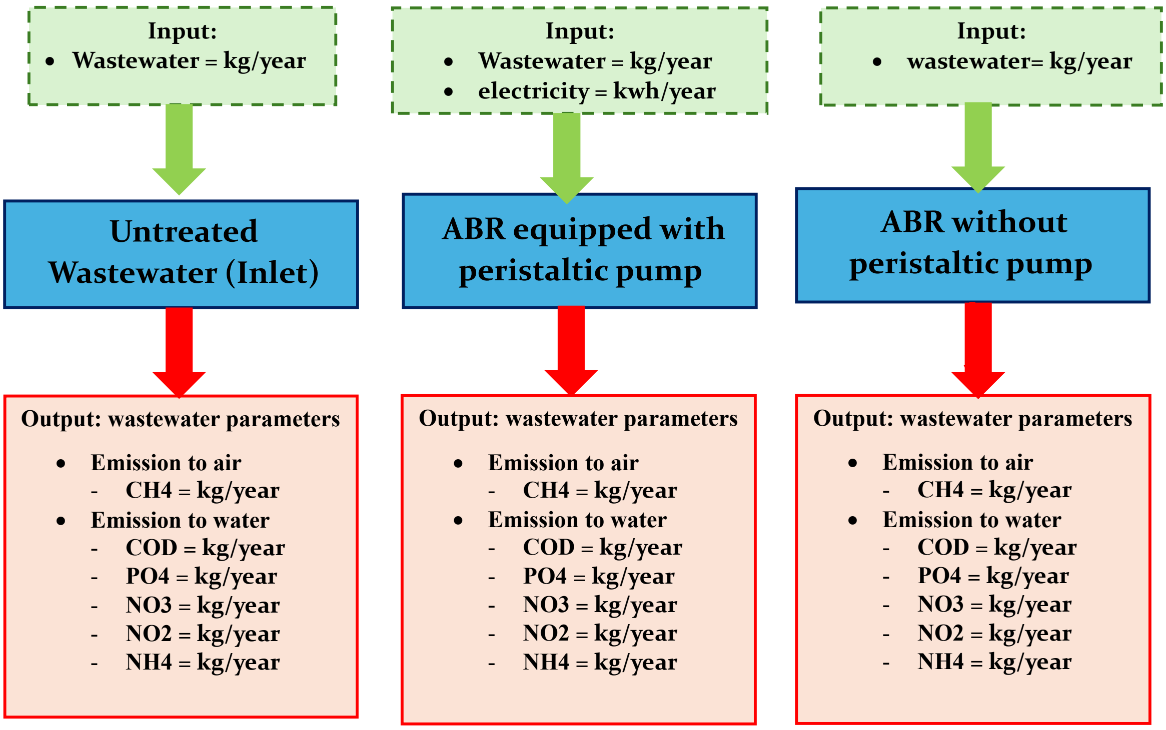

Figure 3. Inventory data of LCA

From Figure 3, the input from the inlet data is the volume of untreated wastewater (inlet) used for the experiment per year, while in the ABR, the input is the volume of wastewater treated in the lab-scale ABR per year. The ABR with pumps also assessed the use of electricity per kWh. The output from the treatment system is treated wastewater, which can be used as clean water and has been tested for PO_4, CH_4, NH_4, NO_3, NO_2, COD, and DO. These input and output data (Figure 3) were used as the basis for calculating the environmental impact analysis that was performed using Simapro 9.1.11, which was used to determine the impact of this system with a flow chart of the inventory stages.

The third stage of the LCA is the impact assessment using the CML-IA baseline method. The impact analysis in the study is classified into 9 categories listed in Table 1.

Table 1. Impact Assessment Using CML-IA Baseline method

Impact Category	Unit	Notes
Global Warming Potential	kg CO_2 eq	The result of GHG emissions expressed in terms of global warming impact (GWP) over one hundred years (in units of CO_2 equivalents).
Eutrophication	kg PO_4 eq	One of the effects of emissions of water results in a decrease in the amount of oxygen expressed in units of PO_4 equivalent (PO_4 ek).
Photochemical Oxidation	kg C_2H_4 eq	measuring the impact of Emissions of volatile organic compounds (VOCs) and nitrogen oxides (NO_x) can cause ozone, which is harmful to air quality and human health.
Abiotic Depletion	MJ	The danger of human-caused depletion or exhaustion of nonrenewable natural resources is used to assess a product's or process's life cycle sustainability.
Human Toxicity	kg 1.4-DB eq	Measurement of environmental consequences associated with a product's or process's ability to harm human health through exposure to hazardous substances.
Aquatic Ecotoxicity	kg 1.4 5Db-Eq	measurement of environmental impacts related to the potential of a product or process to damage aquatic ecosystems (such as rivers, lakes, or the sea).
Terrestrial Ecotoxicity	kg 1.4 Db-Eq	evaluate the impact of products or processes on the health and sustainability of terrestrial ecosystems.
Acidification	kg SO_2 eq	Quantify the potential long-term impacts of acidification caused by products or processes specifically related to soil and water acidification.
Ozone Layer Depletion	kg CFC-11 Eq	The risk of depletion or exhaustion of non-renewable natural resources is emissions of CFC-11, which causes the destruction or depletion of stratospheric ozone and lowers the ability of ozone to block ultraviolet (UV) radiation from entering the atmosphere caused by human actions and is used to assess the long-term viability of a product or process.

From Table 1, the CML-IA baseline method includes abiotic depletion, aquatic ecotoxicity, ozone layer depletion, photochemical oxidation, human toxicity, eutrophication, global warming, terrestrial ecotoxicity, and acidification (Raketh et al., 2024). There are two stages of impact assessment: characterization and normalization data. Characterization data refer to the processing and evaluation carried out to measure the influence of each inventory component on various predetermined environmental impact categories (Ayu and Purwaningsih, 2024). Normalization data describe the contribution of each type of impact to all environmental issues and produce the same unity for each type of impact (Handriani and Pharmawati, 2024).

The final stage of the LCA is the interpretation of the results of the ABR impact assessment. The graphs can conclude the impact assessment, providing future interpretations and alternatives to be applied for the improvement of the system (Shi and Yan, 2024). The interpretation data will be interpreted according to the results of the impact assessment stage by evaluating and analyzing the efforts that can be made for improvement (Sukmawan et al., 2024).

3. Result and Discussion

3.1 Inventory Data & Modelling Treatment

The first scenario of the LCA was to assess the impact of untreated wastewater (inlet). The data were summarized and accumulated based on units per year. Table 2 summarizes the accumulated inventory data, and Figure 4 shows a flowchart of the inventory data.

Table 2. Inventory summary of treatment data untreated wastewater (inlet)

Input	Material & Substances	Amount	Unit
Input Raw Material	Wastewater	5,139,200	kg /year
Output Emission	**Material & Substances**	**Amount**	**Unit**
Emission to Air	CH_4	2,374.0544	kg /year
Emission to Water	PO_4	11.342	kg /year
	NH_4	23.290	kg /year
	NO_2	0.801	kg /year
	NO_3	16.431	kg /year
	DO	9.306	kg /year
	COD	843.91	kg /year

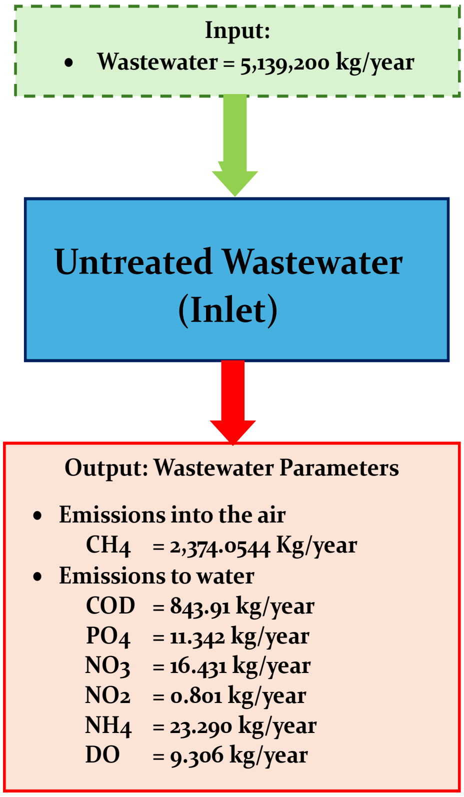

Figure 4. Inventory Flow of the Treatment Data of Untreated Wastewater

Table 2 and Figure 4 show the first treatment; the input was untreated wastewater (inlet) with a total amount of 5,139,200 kg/year. In its output, the wastewater will produce emissions to the environment as CH_4 with the amount of 2,374.0544 kg /year. CH4 production in untreated wastewater was higher than that in treated wastewater. In the process of CH4 production from wastewater, CH4 can reach significant concentrations, with an average of 85% from untreated wastewater (Du et al., 2018). The concentration of CH4 in domestic wastewater can vary significantly depending on the treatment conditions and source of the wastewater. CH4 emissions from untreated wastewater range from 3 to 7 kg CH4 m^3, which is much higher than the CH4 concentration typically found in wastewater entering treatment plants, which ranges from 0.1 to 5 g per cubic meter (Foy et al., 2023). Research by Selvarajan et al., (2021) also showed that the CH4 quality of domestic wastewater can be affected by several factors. These include the type of wastewater generated and the treatment method. Then, the emissions into the water can be measured and tested from the results of wastewater analysis such as PO_4 of 11.342 kg /year, NH_4 by 23,290 kg /year, NO_3 by 16,431 kg /year, NO_2 by 0.801 kg /year, COD by 843.91 kg /year, and DO by 9,306 kg /year, respectively. The concentrations of these substances vary depending on the location and treatment used. Wastewater can cause water pollution by releasing harmful contaminants if not managed properly (Widyarani et al., 2022). Research by Niu et al., (2022) showed that the contribution of domestic wastewater to water pollution was higher, with NO2 and NO levels reaching 1489 mg/L. Domestic wastewater often contains high levels of organic matter, which can lead to water quality degradation if discharged directly into the environment without adequate treatment. The importance of these water quality analyses in assessing the impact of domestic wastewater on aquatic ecosystems has proven that water pollution can affect human health and ecosystems as a whole (Omer, 2020). The second and third scenarios were the assessment of lab-scale ABR equipped with a peristaltic pump and the ABR without a pump. Table 3 summarizes the accumulated inventory data, and Figure 5 presents a flowchart of the inventory data.

Table 3 and Figure 5 show the input data for ABR treatment with a total amount of 19,345 kg/year. For ABR equipped with peristaltic pumps, the input data was the electricity usage of 817.6 kWh/year. In its output, the wastewater produced emissions to the environment as CH_4 of 7.6799 kg/year. CH4 production in treated effluent showed lower concentration. ABR systems can produce CH4-rich biogas, with CH4 concentrations ranging from 55% to 70% (Callahan, 2023). Organic loading rate and effluent CH4 recirculation also affect CH4 production yield, indicating that the system can be optimized to increase CH4 yield (Raketh et al., 2023). Then emissions into the water can be measured and tested from the results of wastewater analysis such as PO_4 of 0.00594 kg /year, NH_4 of 0.0651 kg /year, NO_3 of 0.0722 kg /year, NO_2 of 0.00958 kg /year, COD of 1.3611 kg /year, and DO of 0.0468 kg /year, respectively.

Table 3. Inventory summary of treatment data using ABR

Input	Material & Substances	Amount	Unit
Input Raw Material	Wastewater	19,345	kg /year
Electricity (e.g. electricity pump)	Electricity (e.g. electricity pump)	817.6	kwH/year
Output Emission	**Material & Substances**	**Amount**	**Unit**
Emission to Air	CH4	7.6799	kg /year
Emission to Water	PO4	0.00594	kg /year
	NH4	0.0651	kg /year
	NO2	0.00958	kg /year
	NO3	0.0722	kg /year
	DO	0.0468	kg /year
	COD	1.3611	kg /year

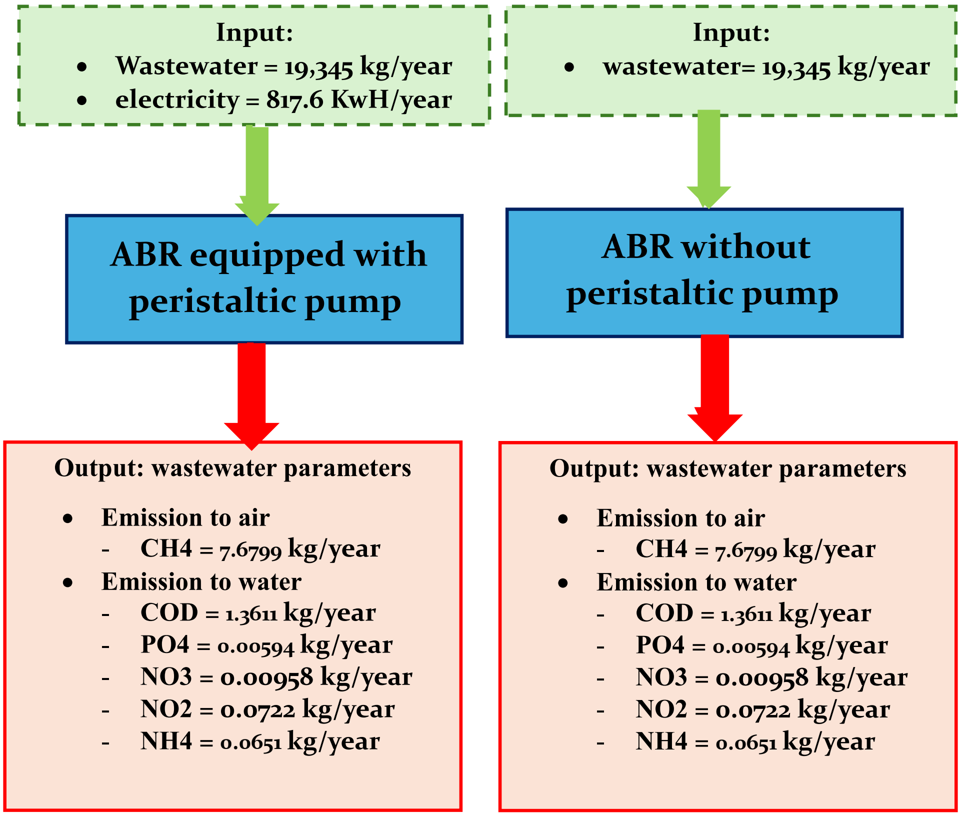

Figure 5. Inventory flow of the treatment data abr equipped with & without peristaltic pump

3.2 Impact Assessment

3.2.1 Untreated Wastewater

The results of the first scenario impact assessment are untreated wastewater (inlet); in this scenario, the results of environmental impacts are shown in Table 4. The impact was analyzed through two stages: characterization (Table 4) and normalization (Figure 6).

Table 4. Characterization of impact assessment data untreated wastewater (inlet)

Impact Category	Amount	Unit
Global Warming	7.56 E4	kg CO2 --- eq
Eutrophication	39.3	kg PO4 --- eq
Photochemical Oxidation	16.2	kg C2H4 --- eq

Figure 6 revealed the three most significant impacts of the normalization data resulting from untreated wastewater (inlet). The largest impact was global warming, with 7.56 E4 kg CO2—eq (GWP100a) and normalization of 1.51E-08, followed by eutrophication and photochemical oxidation. Untreated wastewater can increase GHG yields from CH4 and contribute to global warming impacts. CH4 has 28 times the GWP of CO_2, which is one of the leading gases produced from untreated wastewater (Du et al., 2018). The amount of CH_4 relates to the composition of the wastewater, the process of its decomposition, and the impact on the environment. The inorganic and organic compounds in untreated wastewater can produce GHG such as CH4 and CO2 during their decomposition in the environment which leads to increased GHG concentrations in the atmosphere, which is one of the leading causes of global (Herman, 2023).

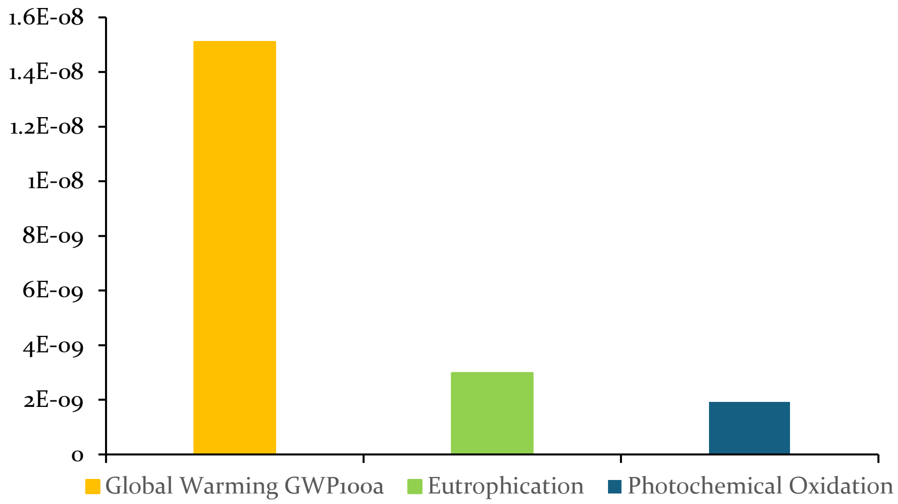

Figure 6. Normalization Graph of Impact Assessment Data Untreated Wastewater

Moreover, eutrophication impact was shown at 39.3 kg PO4—eq and 2.98E-09 for characterization and normalization, respectively. Eutrophication is an increase in nutrients (Nitrogen and Phosphorus) in the water that causes excessive algae growth affects water quality and also causes public health problems (Lam et al., 2022). The eutrophication can lead to the spread of disease, disrupt aquatic ecosystems, and cause excess algae growth which reduces oxygen levels in the water and adversely affects aquatic life (Bahi et al., 2020, Oktarina, 2021). The impact of CH4 on the environment is more potent than CO2 (Pagoray et al., 2021).

Photochemical oxidation with a value of 16.2 kg C2H4—eq and of 1.91E-09 for characterization and normalization, respectively also show a potential threat to the environmental impact, such as a decreasing water quality and ecosystems, and public health. Untreated wastewater can increase the potential for photochemical oxidation by degrading water quality (Nugroho et al., 2022). Photochemical oxidation occurs when organic compounds in wastewater are exposed to UV light from the sun, which can trigger chemical reactions that produce reactive species such as free radicals (Prasetyo, 2021).

3.2.2 Treatment ABR Without Peristaltic Pump

The results of the second scenario impact assessment are ABR without a peristaltic pump; in this scenario, the environmental impact results are shown in Table 5. The impact results go through two stages characterization (Table 5) and normalization (Figure 7).

Table 5. Characterization of ABR impact assessment data of abr without peristaltic pump

Impact Category	Amount	Unit
Global Warming	215	kg CO_2 --- eq
Eutrophication	0.0461	kg PO_4 --- eq
Photochemical Oxidation	0.0065	kg C_2H_4 --- eq

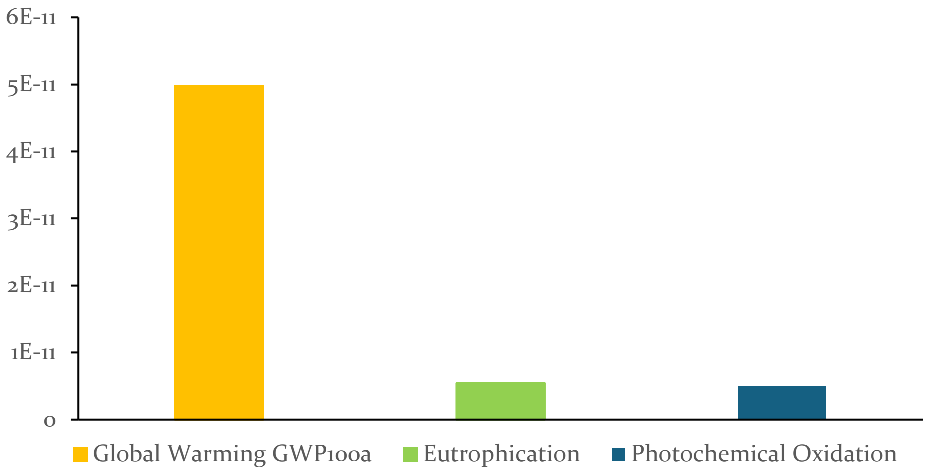

Figure 7. Normalization graph of impact assessment data of ABR without peristaltic pump

Figure 7 revealed the three most significant impacts of the characterization data resulting from ABR treatment equipped with a peristaltic pump. The most significant impact is global warming with 215 kg CO_2-eq (GWP100a) and normalization of 4.98E-11, followed by eutrophication and photochemical oxidation. Without a pump, ABR dramatically lowers GHG emissions, mainly CH_4, which may lessen the effects of global warming (Wang et al., 2021). Each ABR reactor compartment contains a variety of stages that are regulated by distinct microbial communities. Research shows that ABR can facilitate the separation of acetogenesis and methanogenesis processes, which allows for increased CH_4 production efficiency (Vuitik et al., 2019). ABR still produces biogas with a rich CH_4 content (55-70%), which provides an effective waste treatment solution and renewable energy (Callahan, 2023). Although ABR offers an efficient solution for wastewater treatment, it is important to manage the effects of GHG emissions, especially CH_4, to minimize the impact on global warming.

Moreover, the impact of eutrophication was shown at 0.0461 kg PO_4-eq and 5.44E-12 for characterization and normalization, respectively. ABR without a peristaltic pump decreased the eutrophication impact. Anaerobic digestion, often used to treat organic waste, can produce by-products rich in N and P (Lee, 2023). Furthermore, phase separation in anaerobic systems, such as in two-phase reactors, can improve process efficiency and optimize conditions for bacterial growth required in the methanogenesis stage (Orner et al., 2022). Anaerobic increases biogas production and reduces the concentration of P and N nutrients in the final wastewater, thus reducing the risk of eutrophication impacts.

Photochemical oxidation with a value of 0065 kg C_2H_4-eq and 4.97E-12 for characterization and normalization also shows a potential threat to the environmental impact. In ABR, the incoming effluent stream is divided into several compartments by baffles, which create favourable conditions for different microbial growth, increase the effluent treatment rate, and reduce the impact of photochemical oxidation (Pang, 2023). Emissions of ozone-forming compounds from ABR can affect air quality and public health, ozone, for example, formed from the reaction between N_2O and reactive hydrocarbons in sunlight, can cause respiratory problems and damage crops (Hutabarat, 2023; Mohd Rashid and Liu, 2020). Through this, ABR without a peristaltic pump has a lower environmental impact and can potentially reduce GHG, eutrophication, and photochemical oxidation.

3.2.3 Treatment ABR equipped with peristaltic pump

The results of the second scenario impact assessment are ABR equipped with a peristaltic pump; in this scenario, the results of environmental impact are shown in Table 6. The impact results go through two stages characterization (Table 6) and normalization (Figure 8).

Table 6. Characterization of ABR Impact Assessment Data of ABR Equipped With Peristaltic Pump

Impact Category	Amount	Unit
Aquatic Ecotoxicity	143,000	kg 1.4 Db-Eq
Abiotic Depletion of fossil fuel	5,870	MJ
Global Warming GWP100a	684	kg CO_2 --- eq
Human Toxicity	46.6	kg 1.4 Db-Eq
Aquatic Toxicity	7.92	kg 1.4 Db-Eq
Acidification	1.19	kg SO_2 --- eq
Terrestrial Ecotoxicity	0.392	kg 1.4 Db-Eq
Eutrophication	0.326	kg PO_4 --- Eq
Photochemical Oxidation	0.0923	kg C_2H_4 --- Eq
Ozon Layer Depletion	0.0000248	kg CFC-11 Eq
Abiotic Depletion	0.00000294	kg Sb --- Eq

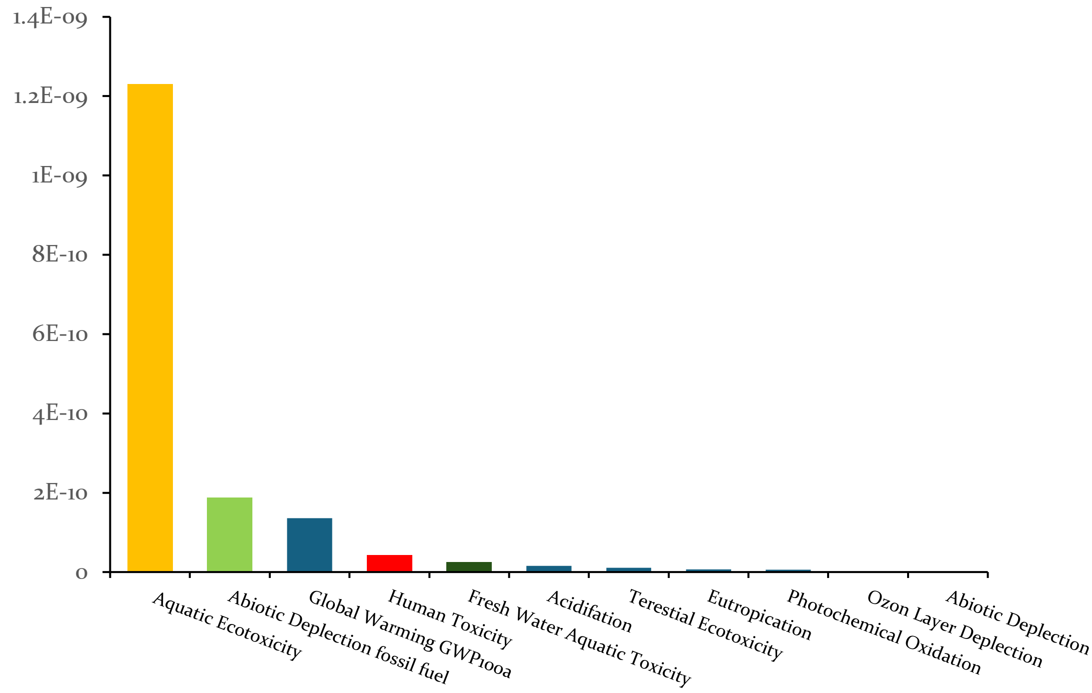

Figure 8. Normalization graph of impact assessment data of ABR equipped with peristaltic pump

Figure 8 revealed the ABR equipped with a peristaltic pump there are eleven potential impacts and three most significant impacts. The ABR equipped with peristaltic pumps has a more complex environmental impact. These impacts result from the electricity use and energy from the peristaltic pump. The impact of ABRs equipped with peristaltic pumps is caused by the system's use of electricity and energy. The use of electricity is an important factor because it can affect the efficiency of the process and the environmental impact of GHG emissions produced (Ar Rachmah et al., 2020). This shows that despite using electricity in the treatment process, there is still a need to improve the effectiveness and efficiency of the technology used to minimize the environmental impact.

The most significant impact is aquatic ecotoxicity with 143,000 kg 1.4 Db-Eq and normalization of 1.23E-09 followed by abiotic depletion of fossil fuel, global warming (GWP100a), and human toxicity. Wastewater pollution has serious consequences for ecosystems. Wastewater from sewage treatment plants can cause immobilization and death of aquatic organisms, with varying degrees of toxicity depending on the type of wastewater. One of the main effects of this pollution is eutrophication, which can reduce water quality, disrupt aquatic life, and also cause mass mortality of organisms due to decreased oxygen levels in the water (Kateb et al., 2018; Tuholske et al., 2021). Furthermore, the presence of effluents, such as the heavy metal content discussed by Bekeowei and Bariweni, (2022), can cause toxic effects that accumulate in the food chain and ultimately affect human health through the consumption of contaminated seafood.

Moreover, the impact of abiotic depletion of fossil fuel was shown at 5,870 MJ and 1.87E-10 for characterization and normalization, respectively. One of the main drivers of fossil fuel depletion is ABR electricity use. Abiotic depletion, specifically related to fossil fuels, refers to reducing non-renewable mineral and energy resources, which contributes to environmental degradation and climate change (Ghannadzadeh and Tarighaleslami, 2019). Using fossil fuels in engines produces pollutants such as NOx and PM (Frhan Al-Abboodi and Ridha, 2023). With almost 2 billion tons of CO_2 produced in 2021, using fossil fuels or electricity has greatly increased CO_2 emissions (Alami et al., 2022). This implies that the abiotic depletion of fossil fuels impacts the ecosystem, human health, and energy supply.

Human toxicity with a value of 46.6 kg 1.4 Db-Eq and 4.61E-11 for characterization and normalization, respectively also show a potential threat for the environmental impact. In wastewater, micropollutants like heavy metals can cause serious health effects, including neurotoxicity and nephrotoxicity (Sakina et al., 2023). Such heavy metals can also cause oxidative stress, contributing to organ damage and metabolism (Abd Elnabi et al., 2023). In addition to heavy metals, toxic organic compounds such as polyaromatic hydrocarbons (PAHs) and phenols are also harmful wastewater constituents. PAHs, which are known carcinogens, can accumulate in human and animal tissues and cause various health problems, including carcinogenic effects (Dan et al., 2023; Joshi et al., 2017). Wastewater that can accumulate in the food chain will have a negative and increasing impact on human health (Khalid et al., 2018; Othman et al., 2021). Other impacts are aquatic toxicity of 7,92 kg 1.4 Db-Eq; acidification of 1,19 kg SO_2-eq; terrestrial ecotoxicity of 0,392 kg 1.4 Db-Eq; eutrophication of 0,326 kg PO_4-Eq; photochemical oxidation of 0,0923 kg C_2H_4-Eq; and the last two smaller impacts are ozone layer depletion and abiotic depletion of 0.0000248 kg CFC-11 Eq and 0.00000294 kg Sb --- Eq.

3.3 Data Interpretation

3.3.1 LCA Comparison Analysis

The LCA comparison of untreated and treated wastewater at UM reported a similar potential impact on the environment which are global warming, eutrophication, and photochemical oxidation as shown in Figure 9.

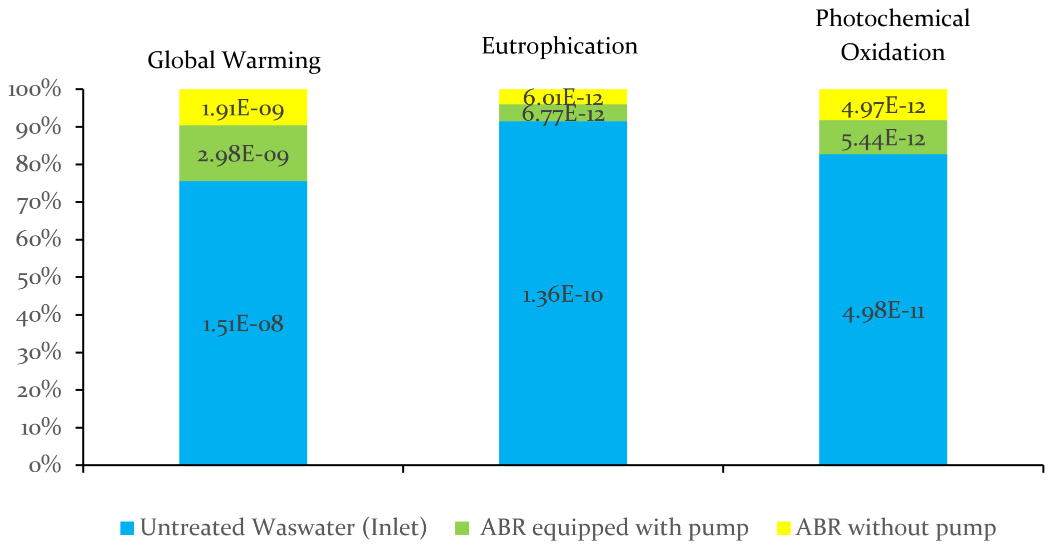

Figure 9. LCA comparison of differences treatment

The interpretation of ABR without a pump shows that the reduction of global warming impact is lower than the ABR equipped with a peristaltic pump with numbers of 2.98E-09 to 1.91E-9 for ABR treatment. While untreated wastewater (inlet) was higher at 1.51E-08. GWP in this system originated from CH_4, in which the total potential GWP results are heavily reliant on material, emission inputs, and energy. (Lei et al., 2024). Wastewater treatment using ABR has been shown effective in reducing pollutants but GHG emissions from the anaerobic process must be considered. This emphasizes the need for strategies to capture CH_4 generated during the treatment process (Ullah et al., 2022). An important issue in climate change is the reduction of GHG emissions or recovering renewable energy from wastewater treatment. Untreated waste has the potential to increase GHG emissions (Camargos Mesquita, 2023) but it may be reduced by the treatment. Comparison between untreated and treated wastewater shows different levels of global warming, eutrophication, and photochemical oxidation.

In the case of eutrophication, the interpretation results of the treatment using ABR without pump show that the impact is lower than the treatment using ABR equipped with pump, from 6.77E-12 to 6.01E-12, and both treatments are significantly lower than untreated wastewater (inlet), which is 1.36E-10. The impact of eutrophication is directly related to the N and P content in wastewater (Pranta and Mawlana

Bhashani, 2023). The impact of eutrophication due to wastewater pollution in waters such as freshwater lakes, rivers, coasts, and reservoirs contributes to the reduction of access to consumable water and affects the supply of drinking water for humans and ecosystems (Dong et al., 2023). NO2, NO3, and PO4 are some of the most important constituents in domestic wastewater that can cause eutrophication if they are not properly managed. ABR, as described by (Zhang and Peng, 2022), is an efficient low-cost technology for treating wastewater. The anaerobic process not only reduces the concentration of pollutants but also reduces emissions that contribute to climate change (Zhao, 2024). Untreated wastewater is also a major source of P and N to the ocean, contributing to coastal eutrophication (Do-Hee et al., 2019).

Similar results were also shown for photochemical oxidation showing that the reduction in the impact of photochemical oxidation ABR without pump use is lower than the ABR equipped with a pump, from 5.44E-12 to 4.97E-12, and both treatments are significantly lower than untreated wastewater (inlet), which is 4.98E-11. The impact of photochemical oxidation due to water pollution comes from the content of NO_2, COD, CH4, and others. Photochemical oxidation has a significant impact on environmental quality, particularly in the context of wastewater. The difference between treated and untreated wastewater (inlet) plays an important role in determining the extent of photochemical oxidant formation and its impact on the environment. The increase in pollutants from photochemical oxidation, including SO_2 and NO_x, can cause acid rain that lowers water pH (Bouwman et al., 2023). Photochemical oxidation can also increase the concentration of PO4 and NO3 in water, leading to excessive algal growth. The excessive growth of algae can cause organisms to die and damage aquatic ecosystems (Sedyaaw et al., 2024). The decline in water quality caused by the impact of photochemical oxidation can threaten biodiversity and disrupt the food chain in aquatic ecosystems (Reichelt-brushett, 2023). Photochemical oxidants, including ozone and NO3, are formed by solar oxidation of atmospheric precursors, including NOx and VOCs. These oxidants can cause adverse health effects and damage the environment (Shen et al., 2023). Wastewater management strategies that incorporate treatment processes, such as ABR or photocatalysis, can reduce these impacts.

A comparison between untreated wastewater and treatment with ABR shows that ABR contributes significantly to the reduction of environmental impacts. The use of ABR shows significant potential to reduce environmental impact through increased treatment efficiency. ABR not only provides a solution for more efficient wastewater treatment but also contributes to environmental sustainability by decreasing the carbon footprint of the wastewater treatment process.

4. Conclusions

Using the Simapro 9.1.11 software with the CML-IA baseline method and gate-to-gate scope, the lab-scale LCA study of ABR for domestic wastewater treatment on the UM campus shows that the environmental impact generated from ABR treatment is much lower and better than untreated wastewater (inlet). ABR equipped with a peristaltic pump and ABR without a peristaltic pump have different environmental impacts. This is because the ABR system requires electricity to pump the flow through a peristaltic pump.

Global warming, eutrophication, and photochemical oxidation are the largest effects of LCA on this ABR. The global warming impact of ABR shows figures of 2.98E-09 and 1.91E-9, which are much smaller than the untreated wastewater (inlet) figure of 1.51E-08. The lower GWP indicates the importance of ABR in reducing GHG emissions compared to untreated wastewater (inlet). The eutrophication impact of ABR shows figures of 6.77E-12 and 6.01E-12, much smaller than the untreated wastewater (inlet) of 1.36E-10. The lower eutrophication impact indicates the importance of ABR in contributing to the reduction of access to consumable water and its impact on the supply of drinking water for humans and ecosystems. The photochemical oxidation impact of ABR shows figures of 5.44E-12 and 4.97E-12, much smaller than the untreated wastewater (inlet) of 4.98E-11. The effective and lower photochemical oxidation impact highlights the importance of ABR in protecting biodiversity, which can disrupt the food chain in aquatic ecosystems. In this study, the scope of the LCA of ABR is limited to the treatment system only. Therefore, further research on the LCA of campus domestic wastewater processing can be developed in the future.

The research can expand its scope to provide further recommendations, starting from the material extraction process to the processed ABR results that can be redistributed. This could also include the use of alternative energy sources such as renewable energy solar panels or more environmentally friendly renewable energy sources.

Acknowledgement

The author expresses gratitude to the Ministry of Higher Education, Research, and Technology of the Republic of Indonesia for the funding support through the Directorate of Research, Technology, and Community Service (DRTPM) with contract number 11.6.44/UN32.14.1/LT/2024. The author also thanks the Department of Civil Engineering and Planning, Faculty of Engineering, Universitas Negeri Malang for the support of facilities and cooperation provided during the implementation of this research.

References

Abd Elnabi, M.K., Elkaliny, N.E., Elyazied, M.M., Azab, S.H., Elkhalifa, S.A., Elmasry, S., Mouhamed, M.S., Shalamesh, E.M., Alhorieny, N.A., Abd Elaty, A.E., Elgendy, I.M., Etman, A.E., Saad, K.E., Tsigkou, K., Ali, S.S., Kornaros, M. and Mahmoud, Y.A.G., 2023. Toxicity of heavy metals and recent advances in their removal: A review. Toxics, 11.

Alami, A.H., Alasad, S., Aljaghoub, H., Sayed, E.T., Shehata, N., Rezk, H. and Abdelkareem, M.A., 2022. Emerging technologies for enhancing microalgae biofuel production: Recent progress, barriers, and limitations. Fermentation, 8.

Ar Rachmah, A.N., Fauzi, A.M. and Bustami, B., 2020. Life cycle assessment komoditi perikanan di Muncar Banyuwangi, Jawa Timur. Jurnal Standardisasi, 22, p.245.

Ayu, F.D. and Purwaningsih, R., 2024. Pengukuran tingkat eko-efisiensi produksi kain motif batik dengan teknik screen printing menggunakan metode life cycle assessment (LCA). Industrial Engineering Online Journal, 13, pp.1–7.

Bahi, Y., Akhssas, A., Khamar, M., Bahi, L. and Souidi, H., 2020. Estimation of greenhouse gas (GHG) emissions from natural lagoon wastewater treatment plant: Case of Ain Taoujdate-Morocco. E3S Web of Conferences.

Bekeowei, R.A. and Bariweni, P.A., 2022. A study of aquatic macrophyte for remediation of chromium and cadmium in wastewater effluents in Yenagoa Metropolis, Niger Delta. Journal of Applied and Natural Science.

BMKG, 2022. Gas rumah kaca. Buletin Gas Rumah Kaca, 2, pp.27–28.

Bouwman, A.F., Vuuren, D.P.V.A.N., Derwent, R.G. and Posch, M., 2023. Of terrestrial ecosystems. Water, Air, and Soil Pollution, pp.349–382.

Callahan, J.L., 2023. Performance analysis of three pilot-scale multi-compartment anaerobic baffled reactors treating domestic wastewater at psychrophilic temperatures in Colorado. Water Environment Research.

Camargos Mesquita, J.L., 2023. Greenhouse gas emission reduction based on social recycling: A case study with waste picker cooperatives in Brasília, Brazil. Sustainability.

Dan, E., Ebong, G.A. and Etuk, H.S., Daniel, I.E., 2023. Carcinogenic potentials of toxic metals and polycyclic aromatic hydrocarbons in Telfairia occidentalis and Talinum triangulare impacted by wastewater, Southern Nigeria. Environmental Protection Research.

Do-Hee, K., Begum, M.S., Choi, J.H., Jin, H., Chea, E. and Park, J., 2019. Comparing effects of untreated and treated wastewater on riverine greenhouse gas emissions. APN Science Bulletin.

Dong, Y., Cheng, X., Li, C., Xu, L. and Lin, W., 2023. Characterization of nitrogen emissions for freshwater eutrophication modelling in life cycle impact assessment at the damage level and urban scale. Ecological Indicators, 154, p.110598.

Du, M., Zhu, Q., Wang, X., Li, P., Yang, B., Chen, H., Wang, M., Zhou, X. and Peng, C., 2018. Estimates and predictions of methane emissions from wastewater in China from 2000 to 2020. Earth's Future.

Ferdous, J., Bensebaa, F., Hewage, K. and Bhowmik, P., Pelletier, N., 2024. Use of process simulation to obtain life cycle inventory data for LCA: A systematic review. Cleaner Environmental Systems, 14, p.100215.

Foy, B. de, Schauer, J.J., Lorente, A. and Borsdorff, T., 2023. Investigating high methane emissions from urban areas detected by TROPOMI and their association with untreated wastewater. Environmental Research Letters.

Frhan Al-Abboodi, N.K. and Ridha, H., 2023. Review of compression ignition engine powered by biogas and hydrogen. Power Engineering and Engineering Thermophysics.

GBCI, 2013. Perangkat penilaian GREENSHIP (GREENSHIP Rating Tools). Greenship New Building Versi 1.2, pp.1–15.

Ghannadzadeh, A. and Tarighaleslami, A.H., 2019. Exergetic environmental sustainability assessment supported by Monte Carlo simulations: A case study of a chlorine production process. Environmental Progress & Sustainable Energy, 5.

Handriani, A.A. and Pharmawati, K., 2024. Kajian literatur life cycle assessement (LCA) perkebunan kelapa sawit di Indonesia. In: Prosiding FTSP Series: Seminar Nasional Dan Diseminasi Tugas Akhir 2023. pp. 2024–2031.

Herman, H., 2023. Pendekatan One Health manajemen air limbah rumah pemotongan hewan Kota Tana Paser. Jurnal Teknologi Lingkungan Lahan Basah.

Hu, L., Li, Z., Kong, L., Wei, J., Chang, J. and Shi, W., 2024. Reassessing the greenhouse effect of biogenic carbon emissions in constructed wetlands. Journal of Environmental Management, 354, p.120263.

Hutabarat, D.M., 2023. Pengaruh jenis koagulan dan variasi pH terhadap kualitas limbah cair di Instalasi Pengolahan Air Limbah PT Kawasan Industri Intiland. Distilat Jurnal Teknologi Separasi.

Idrus, R.T., Armiwati, Romadhani, N., Raihan, A. and Ningki, A.N.K., 2024. Pengelolaan air limbah greywater rumah tangga. Vokatek, 02, pp.17–22.

IPCC, 2023. Summary for policymakers: Synthesis report. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, pp.1–34.

Irianto, 2024. 1-5+Sosialisasi+Perubahan+Iklim+Dan+Krisis+Air. Jurnal Pakem Amata, 4, pp.1–5.

Isnanto, B.A., 2024. UNS jadi kampus pertama yang kelola air limbah secara mandiri. Available at: https://news.detik.com/berita/d-3442802/uns-jadi-kampus-pertama-yang-kelola-air-limbah-secara-mandiri.

International Organization for Standardization, 2016. Environmental management – Life cycle assessment: Principles and framework ISO 14040. Geneva: European Committee for Standardization.

International Organization for Standardization, 2017. Environmental management – Life cycle assessment: Principles and framework ISO 14044. Geneva: European Committee for Standardization.

Jang, J., Lim, S., Choe, S.B., Kim, J.S., Lim, H.K., Oh, J. and Oh, D., 2024. Enhanced predictive modeling vs. LCA simulation: A comparative study on CO2 emissions from ship operations. Ocean Engineering, 310, p.118506.

Joshi, D.R., Yu, Z., Gao, Y., Liu, Y. and Yang, M., 2017. Biotransformation of nitrogen- and sulfur-containing pollutants during coking wastewater treatment: Correspondence of performance to microbial community functional structure. Water Research.

Kateb, A. El, Stalder, C., Rüggeberg, A., Neururer, C., Spangenberg, J.E. and Spezzaferri, S., 2018. Impact of industrial phosphate waste discharge on the marine environment in the Gulf of Gabes (Tunisia). PLoS One.

Khalid, S., Shahid, M., Natasha, Bibi, I., Sarwar, T., Shah, A.H. and Niazi, N.K., 2018. A review of environmental contamination and health risk assessment of wastewater use for crop irrigation with a focus on low and high-income countries. International Journal of Environmental Research and Public Health.

KLHK, 2021. Pedoman penyusunan laporan penilaian daur hidup (LCA). Kementerian Lingkungan Hidup dan Kehutanan, pp.1–82.

KLHK, 2024. Laporan inventarisasi gas rumah kaca (GRK) dan monitoring, pelaporan, verifikasi (MPV) 2023. 9.

Lam, K.M., Solon, K. and Jia, M., van Hoek, J.P., 2022. Life cycle environmental impacts of wastewater-derived phosphorus products: An agricultural end-user perspective. Environmental Science & Technology.

Lee, J.H., 2023. Comparison of solubilization treatment technologies for phosphorus release from anaerobic digestate of livestock manure. Water.

Lei, Z., Zheng, J., Liu, J., Li, Q., Xue, J., Yang, Y., Kong, Z., Li, Y.Y. and Chen, R., 2024. Synergic treatment of domestic wastewater and food waste in an anaerobic membrane bioreactor demo plant: Process performance, energy consumption, and greenhouse gas emissions. Water Research, 266.

Mapanget, Pade, G.S., Mangangka, I.R. and Legrans, R.R.I., 2024. Desain IPAL komunal anaerobic baffled reactor (ABR) sebagai unit pengolahan air limbah domestik. Journal Utekno, 22.

Martin, R., De Melo, B., Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muentan, M., Schaaf, E., Becker, W., Monforti-Ferrario, F., Quadrelli, R., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Brandao De Melo, J., Oom, D., Branco, A. and San-Miguel, J., Vignati, E., 2023. GHG emissions of all world countries. Publications Office of the European Union.

Mohd Rashid, S.N. and Liu, Y.-Q., 2020. Assessing environmental impacts of large centralized wastewater treatment plants with combined or separate sewer systems in dry/wet seasons by using LCA. Environmental Science and Pollution Research.

Mustikaningrum, D., Kristiawan, K. and Suprayitno, S., 2021. Emisi gas rumah kaca sektor pertanian di Kabupaten Tuban: Inventarisasi dan potensi aksi mitigasi. Jurnal Wilayah dan Lingkungan, 9, pp.155–171.

Nasrullah, Z. and Rahmayanti, A., 2024. Efektivitas pengolahan air limbah domestik: Pendekatan teknologi ramah lingkungan. Kerja Praktek Lingkungan, 1, p.37.

Niu, C., Zhang, Q., Xiao, L. and Wang, H., 2022. Spatiotemporal variation in groundwater quality and source apportionment along the Ye River of North China using the PMF model. International Journal of Environmental Research and Public Health.

Nugroho, Y.B., Yulistyorini, A. and Mujiyono, M., 2022. Evaluasi kinerja Instalasi Pengolahan Air Limbah (IPAL) PT. Wahana Kreasi Hasil Kencana (WKHK) Tangerang. Jurnal Teknologi Lingkungan.

Omer, N.H., 2020. Water quality parameters.

Orner, K.D., Smith, S., Nordahl, S.L., Chakrabarti, A.R., Breunig, H., Scown, C.D., Leverenz, H. and Nelson, K.L., Horvath, A., 2022. Environmental and economic impacts of managing nutrients in digestate derived from sewage sludge and high-strength organic waste. Environmental Science & Technology.

Othman, Y.A., Al-Assaf, A., Tadros, M.J. and Albalawneh, A., 2021. Heavy metals and microbes accumulation in soil and food crops irrigated with wastewater and the potential human health risk: A metadata analysis. Water.

Pagoray, H., Sulistyawati, S. and Fitriyani, F., 2021. Limbah cair industri tahu dan dampaknya terhadap kualitas air dan biota perairan. Jurnal Pertanian Terpadu.

Pang, B., 2023. Performance evaluation of anaerobic baffled reactor and filter for treating medium-strength wastewater using natural sludge growth and different hydraulic retention times. IOP Conference Series Earth and Environmental Science.

PDDikti, 2024. Statistik perguruan tinggi menurut jenis. Pusat Pangkalan Data Pendidikan Tinggi. Available at: https://pddikti.kemdikbud.go.id/statistik.

Pranta, A.D., Mawlana Bhashani, 2023. Navigating eutrophication in aquatic environments: Understanding impacts and unveiling solutions for effective wastewater management, 05, pp.11–18.

Prasetyo, C. purnomo, 2021. Dampak pencemaran limbah cair industri tenun ikat terhadap kualitas air tanah di Kelurahan Bandar Kidul Kota Kediri. Jurnal Tecnoscienza.

Raketh, M., Kongjan, P., O-Thong, S., Mamimin, C. and Jariyaboon, R., Promnuan, K., 2024. Life cycle assessment (LCA) and economic analysis of two-stage anaerobic process of co-digesting palm oil mill effluent (POME) with concentrated latex wastewater (CLW) for biogas production. Process Safety and Environmental Protection, 192, pp.450–459.

Raketh, M., Kongjan, P., Trably, É. and Samahae, N., Jariyaboon, R., 2023. Effect of organic loading rate and effluent recirculation on biogas production of desulfated skim latex serum using up-flow anaerobic sludge blanket reactor. Journal of Environmental Management.

Reichelt-brushett, A., 2023. Marine pollution — monitoring, management and mitigation.

Sakina, N.A., Sodri, A. and Kusnoputranto, H., 2023. Heavy metals assessment of hospital wastewater during COVID-19 pandemic. International Journal of Public Health Science (IJPHS).

Samuchiwal, S., Naaz, F., Kumar, P., Ahammad, S.Z. and Malik, A., 2023. Life cycle assessment of sequential microbial-based anaerobic-aerobic reactor technology developed onsite for treating textile effluent. Environmental Research, 234.

Sedyaaw, P., Bhaladhare, D.R. and Kawade, S.S., 2024. A review on acid rain it's causes. International Journal of Creative Research Thoughts (IJCRT), 12.

Selvarajan, R., Sibanda, T., Pandian, J. and Mearns, K., 2021. Taxonomic and functional distribution of bacterial communities in domestic and hospital wastewater system: Implications for public and environmental health. Antibiotics.

Shen, Y.-G., Xiao, Z., Wang, Y., Xiao, W. and Yao, L., Zhou, C., 2023. Impacts of agricultural soil NOx emissions on O3 over Mainland China. Journal of Geophysical Research: Atmospheres.

Shi, S. and Yan, X., 2024. Review article a critical review on spatially explicit life cycle assessment methodologies and applications. Sustainable Production and Consumption, 52, pp.566–579.

Sukmawan, Y., Dewi, R., Riniarti, D., Agusta, H. and Sudradjat, S., 2024. Evaluasi dampak lingkungan pada pembibitan kelapa sawit (Elaeis guineensis Jacq.) dengan pendekatan penilaian daur hidup. Jurnal Sumberdaya Alam dan Lingkungan, 11, pp.64–72.

Tuholske, C., Halpern, B.S., Blasco, G., Villasenor, J.C., Frazier, M. and Caylor, K.K., 2021. Mapping global inputs and impacts from of human sewage in coastal ecosystems. PLoS One.

Ullah, N., Zeshan and Badshah, M., 2022. Municipal wastewater treatment with corrugated PVC carrier anaerobic baffled reactor. Water Science & Technology.

UM Green Campus, 2022. UM green campus report 2022. Available at: [suspicious link removed].

UNCRD, 2020. Early release state of plastics waste in Asia and the-pacific - issues, challenges and circular economic opportunities.

Vuitik, G.A., Fuess, L.T., Nery, V. Del and Bañares-Alcántara, R., Pires, E.C., 2019. Effects of recirculation in anaerobic baffled reactors. Journal of Water Process Engineering.

Widyarani, W., Wulan, D.R., Hamidah, U., Komarulzaman, A. and Rosmalina, R.T., Sintawardani, N., 2022. Domestic wastewater in Indonesia: Generation, characteristics and treatment. Environmental Science and Pollution Research.

Yan, Y., Gu, R., Zhu, M., Tang, M., He, Q. and Tang, Y., Liu, L., 2023. Environmental impacts and optimization simulation of aerobic anaerobic combination treatment technology for food waste with life cycle assessment. Waste Management, 164, pp.228–237.

Yilmaz, M., Guven, H., Ozgun, H., Ersahin, M.E. and Koyuncu, I., 2024. The application of life cycle assessment (LCA) to anaerobic technologies for the treatment of municipal wastewater: A review. Process Safety and Environmental Protection, 182, pp.357–370.

Yulistyorini, A., 2021. Post-treatment of anaerobic baffled reactor effluent using modified up-flow anaerobic filter. In: 3rd International Conference of Green Civil and Environmental Engineering (GCEE 2021).

Zhang, L. and Peng, B., 2022. Review on anaerobic digestion and disposal technology of solid waste. Scientific Journal of Technology.

Zhao, K., 2024. Study on the environmental impact and benefits of incorporating humus composites in anaerobic co-digestion treatment. Toxics.

Zhu, J., Li, S., Li, T., Zhu, A., Shao, Y., Yang, Z., Chen, L. and Li, X., 2024. Environmental impact analysis of potassium-ion batteries based on the life cycle assessment: A comparison with lithium iron phosphate batteries. Journal of Cleaner Production, 483, p.144298.