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Effectiveness of Hybrid Solar Power Plant Integration in Wastewater Treatment: A Sustainable Approach to Water Crisis

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Abstract

This study evaluated the effectiveness of a solar-powered Wastewater Treatment Plant (WWTP) integrated with a water filtration system in improving water quality. This study employed an experimental approach, comparing influent and effluent water quality to determine treatment efficiency. The results showed significant improvements in water parameters, with pollutant removal efficiencies of 31.54% for Total Dissolved Solids (TDS) and 15.22% for pH reduction. The Dissolved Oxygen (DO) increased by 29.41% due to enhanced aeration. However, Electrical Conductivity (EC) increased by 46.07%, indicating the presence of dissolved ions post-treatment. The anaerobic-aerobic process effectively degrades organic pollutants, supported by bacterial activity, while the filtration system enhances water clarity and odor reduction. Despite these positive outcomes, the study has limitations, particularly the lack of Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) measurements, which restricts a comprehensive assessment of organic pollution removal. Future research should incorporate these parameters to provide a more holistic evaluation of wastewater treatment performance.

Keywords: Waste water treatment plant; water filtration system; renewable energy; polutan removal efficiency

1. Introduction

Water resources are essential for life as we know it, in cultivated farmland, sustainability, human consumption, economic development, and environmental systems (Akhtar et al., 2021). High-quality water positively impacts its users, while poor water quality leads to adverse environmental effects, impacting the health and safety of living organisms in the area (Anatolia S.M. Exposto et al., 2021; Ejiohuo et al., 2024). Currently, high-quality water has become increasingly scarce and costly due to society's lack of awareness and concern for water conservation (Indah Lestari et al., 2021). Today, water scarcity has become a significant environmental crisis in many regions worldwide (Jahura et al., 2024). In Indonesia, several water sources are commonly used by people in both urban and rural areas. These sources include springs in mountainous regions, rivers, shallow wells, and deep wells (Setiawan). In urban areas, raw water sources are treated to meet water quality standards before being distributed, although some urban communities independently use well or drilled water (Baddianaah et al., 2024).

Rivers, as a rich source of water, are heavily utilized by communities to meet daily needs. However, in addition to supporting human consumption, rivers are also used for the disposal of solid and liquid waste from industrial activities, households, livestock, workshops, and other businesses (Lee et al., 2020). The discharge of waste containing both biodegradable and non-biodegradable pollutants into rivers places a significant burden on water bodies, leading to severe negative impacts on the health of aquatic organisms and surrounding communities (Mohanaprasadh et al., 2022; Warmadewanthi et al., 2021). The control of water quality and quantity significantly impacts the standard of living of the population. Therefore, providing access to clean drinking water should be recognized as a fundamental human right that is equitably distributed across society. Comprehensive water treatment measures are essential to meet public demand for safe and potable water (Djana, 2023). Alarmingly, approximately 40 percent, or around 90 million Indonesians, are still compelled to use water that is unfit for human health in their daily lives (Setiawan et al., 2024).

The water quality of several rivers in Indonesia is a significant concern (Pratiwi, 2013). This is evidenced by water quality test results conducted by Environmental Offices across various regions, which indicate that the quality of several rivers in Indonesia is highly concerning (Isabella Silalahi et al., 2022). The decline in water quality in these rivers is largely attributed to industrial wastewater from surrounding areas (Akhtar et al., 2021). The decline in water quality in several rivers in Indonesia is primarily attributed to the discharge of industrial wastewater. Some businesses dispose of waste directly into the environment without proper treatment, largely due to insufficient attention to the operation of integrated wastewater treatment plants (WWTP). Integrated WWTPs are typically constructed by the government to mitigate the impact of water pollution from liquid waste. In the city of Makassar, one of the rivers heavily affected by pollution is the Pampang River (Akrim et al., 2024a; Murti et al., 2023).

The Pampang River and Pampang Canal are vital water channels in Makassar, running through the city for approximately 8.4 km in length. Due to its location in densely populated residential areas, the river has become a dumping ground for both household and industrial waste, which has not been properly managed (Akrim et al., 2024b). Consequently, the river suffers from significant pollution, resulting in severely degraded water qualities. This water typically contains substances or materials that pose risks to human health and negatively impact the environment (Akrim et al., 2024a). The water appears dark black in color and emits a strong odor. However, no research has yet been conducted to assess the extent of water pollution in the Pampang River and Canal.

To prevent and mitigate the negative impacts of river pollution caused by liquid and other types of waste, river water quality must be evaluated. A straightforward approach to determine the water quality status is by comparing monitoring results with established water quality standards. According to the Decree of the State Minister for the Environment Number 115 of 2003 concerning Guidelines for Determining Water Quality Status, two methods are used to determine water quality: the storet method and the pollution index method. These methods can categorize water quality as good (not polluted), moderately polluted, or heavily polluted. The results of this evaluation then serve as a basis for decision-making, including the identification of necessary preventive and corrective actions.

Numerous studies have been conducted to develop wastewater treatment plants (WWTPs), such as the application of bioreactor membrane technology, phytoremediation, and bioelectrochemical methods. Additionally, efforts to improve waste processing efficiency have focused on integrating biological processes with smart sensor technology and artificial intelligence. These innovations aim to create environmentally friendly, energy-efficient solutions that are widely applicable to meet the demands of modern waste management (Buraerah et al., 2023).

However, it is well known that WWTPs are designed primarily to treat wastewater before discharging it into rivers, streams, or waterways. To date, there has been developed that, in addition to making water safe for disposal into nature, can also make it reusable for community daily needs, particularly for sanitation purposes. One way to enhance this type of WWTP is by adding a water purification system at the end of the treatment process. This ensures that the water exiting the chlorination tank can be further purified to reduce metal content, odors, and other pollutants. Water purification can be achieved using various materials, such as silica sand, zeolite stone, and activated carbon. According to (Lestari et al., 2022), the use of activated carbon filters is effective in removing remaining suspended solids, organic substances, odors, tastes, and other micropollutants.

However, the operation of Wastewater Treatment Plants (WWTPs) requires a significant amount of electrical energy to power pumps and aerators. Currently, almost all WWTPs rely on electricity from PLN (State Electricity Company); however, operating these systems 24/7 incurs high costs, making it challenging for individuals and agencies to maintain their continuous operation. Furthermore, not all locations have access to PLN's electricity supply, highlighting the need for WWTPs that utilize new renewable energy sources, which are more affordable and environmentally friendly. However, the use of renewable energy-based WWTPs remains relatively uncommon.

Additionally, sustainability has become an urgent national agenda in Indonesia, particularly after the government set targets for carbon emission reduction to address climate change. With abundant solar energy available in tropical regions, this technology presents a significant opportunity to harness natural resources for the treatment of wastewater. By utilizing solar energy to continuously power WWTP, the dependence on conventional electricity, which is largely derived from fossil fuels, can be reduced. This approach also addresses the challenge of high operational costs for WWTPs, which are often a major barrier to effective waste management. Moreover, the location and abundance of sunlight in Indonesia is one of the supporting factors for implementing solar power-based WWTP. Indonesia is very rich in renewable energy with a potential (Langer et al., 2021). Although there is a vast solar energy potential of 3,294.4 GWp in Indonesia, only 0.3 GW, or 0.01% of the total potential, has been utilized(Kharisma et al., 2024). In fact, Indonesia is an equatorial country which should be a leader in developing solar energi (Santika et al., 2020).

Solar-powered wastewater treatment technologies combined with filtration systems represent a major advancement in tackling both water scarcity and energy challenges. As the demand for clean water continues to rise, especially in densely populated urban and suburban areas, ensuring water quality has become a pressing issue. Reliance on rivers as primary water sources has often led to adverse effects due to increasing pollution levels. Solar-powered WWTPs are an energy-efficient and environmentally sustainable solution to address these challenges. This study evaluated the effectiveness of a solar-powered WWTP integrated with a water filtration system, aiming to determine its capability to improve water quality. Ultimately, solar-powered wastewater treatment systems provide a practical model for decentralized water treatment in urban and remote rural areas with limited access to conventional electricity grids.

2. Method

2.1. Time and Location

This study employs an experimental research design. Two types of data were utilized: primary data, which were collected through observations of the research site, documentation, and interviews with local communities around the Pampang River, as well as wastewater sampling from influents and effluents (Umar & Zulaeha, 2020). Secondary data were obtained from relevant agencies, including the existing floor plan of the research site, water flow data, and waste load information.

Data were collected in the Pampang River Basin, located adjacent to Building I at Bosowa University. The processing system was analyzed to determine the appropriate treatment units based on wastewater characteristics. Wastewater treatment units employ physical, biological, and chemical processing systems, which include stages such as equalization and bar screening, settling tank I, anaerobic reactor, aerobic biofilter, maturation pond, and disinfection (Anjana, 2021). The research location is situated at the East Parking Lot of the Bosowa University campus, along the Pampang River in Makassar, Indonesia (7° 02' 47.9" S, 110° 26' 35.9" E), as shown in Figure 1.

Figure 1. Research Location

The Pampang River and Pampang Canal are among the most important water channels for the city of Makassar, stretching approximately 8.4 km through the central part of the city. However, due to their location, predominantly within residential areas, these waterways have become dumping grounds for household and industrial waste that is not properly managed. Consequently, significant pollution has occurred, leading to very poor water quality. Visually, the water appeared dark black and emitted a strong odor. Despite these conditions, no substantial research has been conducted to address or mitigate water pollution levels in the Pampang River. Observations from various points along the river indicate that households and industries are reluctant to adopt wastewater treatment plants (WWTP). This reluctance is primarily due to limited awareness of the benefits of WWTP, the high cost of construction, and the significant energy consumption required for their operation (Akrim, Suparno, et al., 2024).

2.2. Research Flow

The research flow on figure 2 commenced with data collection through direct observation of the Pampang River, followed by interviews with local community members to gain insight into the conditions and challenges related to water quality in the area. A literature review was conducted to establish a scientific foundation for wastewater treatment relevant to the research context. Following the data collection phase, the next step involved designing and constructing a Wastewater Treatment Plant (WWTP) integrated with a filtration system using a biofilter process. This WWTP was designed to treat wastewater using a combination of anaerobic and aerobic processes coupled with filtration to improve the water quality of the Pampang River.

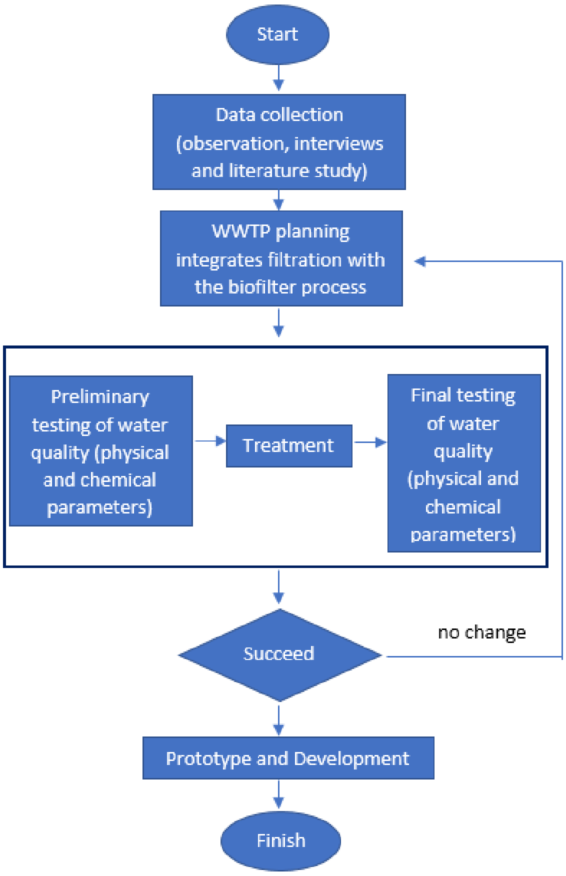

Figure 2. Research Flow

Following WWTP construction, water samples were collected once from both the inlet and outlet of the Pampang River to assess various water quality parameters, including pH, dissolved oxygen (DO), total dissolved solids (TDS), temperature, and electrical conductivity (EC). The collected water was then transferred to an initial storage tank before undergoing treatment in anaerobic and aerobic tanks, which were pre-inoculated with decomposing bacteria to facilitate organic matter breakdown. Subsequently, the treated water was directed to a chlorination tank for pathogen elimination. The final stage involved filtration, where the water passed through a filtration tank containing multiple media, including silica sand (12×20 mesh size) and activated carbon (8×30 mesh size). After the filtration process, water samples were collected and analyzed using the same parameters as the initial tests to evaluate the effectiveness of the treatment process. The final results were then compared with the initial measurements to determine potential system modifications or improvements, such as optimizing the WWTP's configuration, adjusting the filtration tank capacity, or refining the bacterial and chlorine composition for enhanced treatment efficiency. To determine the pollutant removal efficiency in the system, we used the %Removal equation, as shown below using equation (1).

$$\%Removal = \frac{(Inlet - Outlet)}{(Inlet)} x\ 100 \quad (1)$$

3. Result and discussion

3.1. Solar Power-Based WWTP Design Assisted by a Water Filtration System

The type of Wastewater Treatment Plant (WWTP) used in this study is the Biotech/Biofilter system. The Biotech/Biofilter WWTP is a wastewater treatment technology that employs microorganisms on specialized filter media to efficiently decompose organic materials through both anaerobic and aerobic processes. This system offers significant advantages in the efficient degradation of organic pollutants, leading to higher-quality treated wastewater. Additionally, it is environmentally friendly as it minimizes the use of chemicals and energy compared to conventional treatment methods. The Biotech/Biofilter WWTP is an effective and eco-conscious waste treatment solution, utilizing biological processes to naturally break down pollutants, resulting in cleaner and safer wastewater for the environment. The Biotech/Biofilter WWTP operates according to the following water treatment scheme on figure 3.

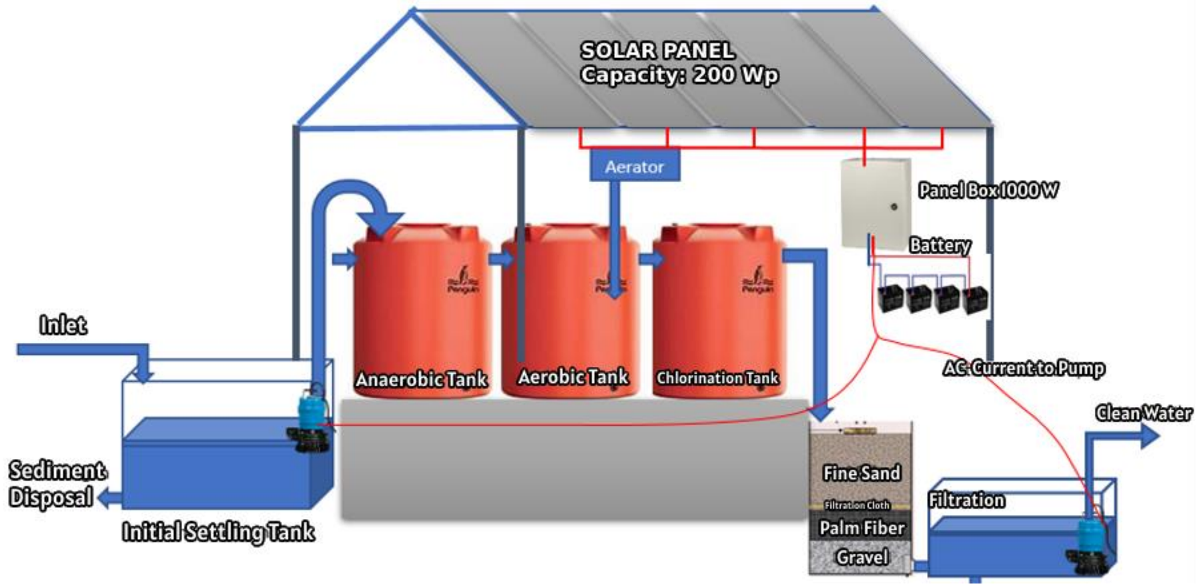

Figure 3. Wastewater treatment process diagram with a solar power-based anaerobic-aerobic biofilter process assisted by water filtration

The development of a Wastewater Treatment Plant (WWTP) using a submersible pump powered by a Hybrid Solar Power Plant (HSPP) aims to establish a more environmentally friendly and energy-independent wastewater treatment system. The system consists of two polycrystalline solar panels, each with a capacity of 100 Wp, arranged at an optimal tilt angle to maximize sunlight absorption throughout the day. The panels are connected in parallel to maintain a stable voltage output while increasing current capacity, ensuring sufficient power for the submersible pump and other electrical components. To enhance reliability, a Maximum Power Point Tracking (MPPT) charge controller was integrated to regulate the energy flow and optimize the battery charging efficiency. The maximum panel efficiency reaches 88.36% at 12:00 PM, with an input power range of 71–82 watts between 09:00 AM and 04:00 PM. The energy generated during peak sunlight hours was stored in a 100 Ah deep-cycle battery, which provided backup power during nighttime or low-sunlight conditions. This design ensures continuous and autonomous operation of the WWTP, reducing dependency on conventional electricity and promoting sustainable wastewater treatment.

The submersible pump in this system functions to circulate wastewater between treatment tanks, including aerobic, anaerobic, chlorination, and filtration units. With a power requirement of approximately 50.5 watts, the pump operates steadily using electricity from the HSPP. The experimental results show that the solar panel output sufficiently meets the pump's energy demand and other electrical components while enabling energy storage for nighttime use. This demonstrates that integrating HSPP technology into WWTPs can reduce dependence on conventional electricity sources and enhance the sustainability of wastewater treatment systems.

At an inflow rate of 800 L/h, the wastewater treatment system achieved a total retention time of approximately 6 h and 23 min, ensuring optimal pollutant removal. The Initial Settling Tank (1,000 L) allows for primary sedimentation with a retention time of 1 hour and 15 minutes, followed by the Anaerobic Tank (1,200 L), Aerobic Tank (1,200 L), and Chlorination Tank (1,200 L), each maintaining a 1 hour and 30 minutes retention period for efficient biological and chemical treatment. The final stage, the Filtration System, now upgraded to 500 L, provides an extended retention time of 37.5 minutes, significantly improving sediment removal and preventing clogging in the fine sand, palm fiber, gravel, and filtration cloth layers. This optimized configuration enhances overall system performance by ensuring adequate contact time for each treatment phase, leading to improved effluent quality.

Before the water enters the initial settling tank, a water quality test is first carried out with the parameters as in table 1. Then in the IPAL unit, the waste water is first channeled into the initial settling tank, to settle mud, sand and suspended organic dirt particles. Apart from being a settling tank, it also functions as a tank for decomposing organic compounds in solid form, sludge digestion (sludge decomposer) and sludge reservoir. The runoff water from the initial settling tank is then channeled to the anaerobic contactor tank (Anaerobic biofilter) in a flow direction from top to bottom. In the anaerobic contactor tank, it is filled with special media made from honeycomb type plastic material. The anaerobic contactor tank consists of two rooms. The decomposition of organic substances in wastewater is carried out by anaerobic or facultative aerobic bacteria (Prisntanto et al., 2015). After several days of operation, a film layer of microorganisms grows on the surface of the filter media. These microorganisms will decompose organic substances that have not had time to decompose in the settling tank (Bella and Rao, 2023; Tauseef et al., 2013).

Wastewater from the anaerobic contactor (biofilter) tank flows into the aerobic contactor tank. In this aerobic contactor tank, a special medium made of honeycomb-type plastic material is used, which is aerated or blown with air so that the existing microorganisms decompose the organic substances in the wastewater and grow and stick to the surface of the medium (Zheng et al., 2013). In this way, waste water will come into contact with microorganisms suspended in water or attached to the surface of the media, which can increase the efficiency of decomposing organic substances, as well as speed up the nitrification process, so that the efficiency of ammonia removal is greater. This process is often called Contact Aeration.

From the aeration tank, water flows to the final settling tank. In this tank, activated sludge containing microorganisms is deposited. In this final settling tank, the waste water is contacted with chlorine compounds to kill pathogenic microorganisms. Chlorine addition can be done using chlorine tablets or with a chlorine solution supplied via a dosing pump. Processed water, namely the water that comes out after the chlorination process, can be directly discharged into rivers or public channels). The waste water is contacted with chlorine compounds to kill pathogenic microorganisms (Al-Sa'ady et al., 2020; Ghernaout, 2017). The water that comes out of the final settling tank will undergo a filtration process using various filtration media such as silica sand, activated carbon, gravel, zeolite and filtration cloth (Sariman and M, 2022). Then a final testing stage is carried out to compare how the water quality compares for each parameter before and after going through the Integrated IPAL which refers to Quality Standard standards. Exposition and discussion of the study results. The advantage of the installation we developed is the integration of solar power into the wastewater treatment plant (WWTP). This integration design plays a crucial role in enhancing the sustainability and cost-efficiency of the system.

The solar-powered system ensures that the necessary aeration process, which is essential for the aerobic stage of wastewater treatment, operates efficiently. Solar energy is used to power air pumps that introduce oxygen into the aerobic biofilter, helping the microorganisms break down organic pollutants. This process is vital for the removal of biodegradable substances from the wastewater. Additionally, the energy provided by solar panels is used to maintain the optimal flow rate of wastewater through the various stages of treatment, from the initial settling tank to the biofilter and final filtration stages. The use of solar power ensures that the system remains operational even in remote or off-grid locations, making it a practical solution for sustainable wastewater management, especially in rural or underserved areas.

The solar-powered WWTP design, coupled with the water filtration system, represents an innovative approach to environmental sustainability. By combining renewable energy with efficient wastewater treatment technology, this design offers a promising solution to the challenges of water pollution and energy consumption. The success of this design lies in its ability to harness natural resources to address environmental concerns while minimizing operational costs and improving the overall system performance.

3.2. Water Test Result

The results of the water quality tests for Pampang River samples before undergoing treatment in the WWTP are presented in Table 1 below:

Table 1. Initial test results of Pampang River Water

Initial Test (Inlet) Before Processing				
Water Quality Meter	**Unit**	**Standard**	**Result**	**SNI**
pH	-	6 - 9	8.28	SNI 6869.11-2019
DO	mg/L	6	6.8	SNI 06-6989.14-2004
Total Dissolved Solids (TDS)	mg/L	1.000	279	SNI 6989.27:2019
Temperature	°C	Dev 3	28,8	SNI 06-6989.23-2005
Electrical Conductivity (DHL)	μmhos/cm	250 - 750	382	SNI 6989.1-2019

Based on Table 1, it can be observed that the Pampang River water exhibits an alkaline pH (above 7). The dissolved oxygen (DO) value of 6.8 mg/L indicates that the water is polluted to some extent. Meanwhile, the total dissolved solids (TDS) value of 279 mg/L, within the 250-300 mg/L range, suggests that the water is of acceptable quality for drinking. Additionally, the water temperature of 28.8°C is above the average, which may influence dissolved oxygen levels and impact the aquatic ecosystem. The electrical conductivity (EC) value of 382 μmhos/cm is still within the quality standards, although it indicates the presence of dissolved ions in the water.

The initial water quality test results from the Pampang River indicate that the water is in moderate condition, with several parameters approaching safe limits. The pH value of 8.28 suggests alkalinity, likely due to household or industrial waste. The DO concentration of 6.8 mg/L is sufficient to support aquatic life, though it remains vulnerable to fluctuations caused by organic pollutants. The TDS level of 279 mg/L and EC of 382 μmhos/cm are within the safe range but point to dissolved ion contamination. The water temperature of 28.8°C, slightly higher than the natural average, may affect the dissolved oxygen levels and the aquatic ecosystem. Overall, these findings suggest that the Pampang River is beginning to experience pollution, though the water quality has not yet reached critical levels.

Table 2. Final test results of Pampang River Water

Final Test (Outlet) After Processing				
Water Quality Meter	**Unit**	**Standard**	**Result**	**SNI**
pH	-	6 - 9	7.02	SNI 6869.11-2019
DO	Mg/L	6	8.8	SNI 06-6989.14-2004
Total Dissolved Solids (Tds)	Mg/L	1.000	191	SNI 6989.27:2019
Temperature	°C	Dev 3	27	SNI 06-6989.23-2005
Electrical Conductivity (DHL)	μmhos/Cm	250 - 750	558	SNI 6989.1-2019

The water quality test results from the Pampang River, as presented in Table 2, show significant changes in several water quality parameters after treatment in the Wastewater Treatment Plant (WWTP).

The pH of the water decreased from 8.28 to 7.02, indicating that the treated water has become more neutral, which is more suitable for aquatic life. This decrease in pH reflects the success of the filtration and biofilter processes in neutralizing the alkaline content in the water, which could have previously been harmful to the organisms residing in the water. The pH removal efficiency was recorded at 15.22%. This reduction in pH is consistent with prior research, which suggests that the use of more active adsorbents can enhance the reduction of pH in water (Pratiwi & Setiorini, 2023). This process helps mitigate the negative effects of alkaline-based pollutants, making the water safer for aquatic life. Tabel 3 show percentage of removal each parameter

Table 3. %Removal Each Parameters

%REMOVAL					
Water Quality Meter	**Unit**	**Standard**	**Inlet**	**Outlet**	**%Removal**
pH	-	6 - 9	8.28	7.02	15.22
DO	mg/L	6	6.8	8.8	-29.41
Total Dissolved Solids (TDS)	mg/L	1.000	279	191	31.54
Temperature	°C	Dev 3	28.8	27	6.25
Electrical Conductivity (DHL)	µmhos/cm	250 - 750	382	558	46.07

Additionally, there was a notable increase in the concentration of dissolved oxygen (DO), from 6.8 mg/L to 8.8 mg/L. This increase indicates that the aeration and biofilter processes effectively elevated the oxygen content in the water, which is essential for supporting the survival of microorganisms and other aquatic organisms. However, this resulted in a negative removal efficiency of -29.41%, which signifies oxygen enrichment rather than removal. The increase in DO also signifies an improvement in water quality, as higher oxygen levels facilitate the breakdown of organic materials, thereby enhancing the overall health of the aquatic ecosystem. Furthermore, the increase in oxygen levels demonstrates that the treatment system is effectively providing the necessary conditions for microorganisms in the water to decompose organic matter.

In addition to the increase in dissolved oxygen (DO), there was a significant decrease in Total Dissolved Solids (TDS), from 279 mg/L to 191 mg/L. This decrease indicates that the filtration process effectively reduced the concentration of dissolved particles that could degrade water quality. The TDS removal efficiency was recorded at 31.54%, indicating that a substantial proportion of dissolved solids was successfully eliminated through filtration. With the TDS now falling within the 150-250 mg/L range, the water is classified as safe for human consumption. This suggests that the filtration system, particularly one that relies on activated carbon and other media, is performing well in removing dissolved compounds that could be harmful to human health if ingested. The substantial reduction in TDS is consistent with findings from other studies, which demonstrate that activated carbon is effective in reducing TDS by adsorbing dissolved particles in water (Lestari et al., 2022).

However, despite the significant improvements in water quality parameters, the Electrical Conductivity (EC) value increased from 382 µmhos/cm to 558 µmhos/cm. This increase in EC reflects a rise in the concentration of dissolved ions in the water, likely due to the presence of dissolved metal or salt compounds introduced during the treatment process. The increase in EC resulted in a negative removal efficiency of -46.07%, indicating an accumulation of conductive particles. Although this increase does not directly indicate a decline in water quality, further investigation is necessary to understand the source of these dissolved ions and their potential impact on water quality. As noted by Astuti (2018), an increase in the concentration of ions in water can lead to higher electrical conductivity, which is linked to the presence of dissolved electrolytes.

Additionally, although the water temperature slightly decreased from 28.8°C to 27°C, this helped maintain a more stable dissolved oxygen level and slowed down chemical reactions that could otherwise affect water quality. The temperature reduction was recorded at 6.25%, indicating a slight but beneficial cooling effect. Overall, while there was a slight increase in dissolved ions, the treatment process indicated that the system was effective in improving the water quality of the Pampang River, although further analysis is needed to address some remaining concerns.

4. Conclusion

The integration of solar-powered systems with wastewater treatment enhances energy efficiency and sustainability, providing a reliable and eco-friendly solution for pollution reduction while minimizing operational costs and dependence on conventional energy sources. Additionally, studies indicate that wastewater treatment utilizing an anaerobic-aerobic process is highly effective in reducing pollution levels, achieving pollutant removal rates of 85–95%, as this process promotes the degradation of toxic compounds through anaerobic and aerobic bacterial activity, transforming harmful substances into less hazardous forms. The incorporation of purification and filtration systems further improves pollution control and odor reduction; however, successful implementation depends on appropriate system design, effective monitoring, and regular maintenance. Despite these promising results, the study lacks Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) analyses, which are critical for accurately assessing organic pollution levels during the wastewater treatment process.

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