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Development of Biofiltration-Based Wastewater Treatment Technology and Smart Sensors

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Abstract

The problem of wastewater pollution due to domestic activities and small industries is still a serious challenge in various regions, especially in developing countries such as Indonesia. Existing wastewater treatment technologies tend to be less efficient, expensive, and unresponsive to real-time changes in water quality. This research aims to develop a biofiltration-based wastewater treatment system integrated with smart sensors based on the Internet of Things (IoT). The research method used is Research and Development (R&D), with stages of prototype design, laboratory tests, sensor validation, and limited field tests. The developed prototype consists of a biological filtration medium (gravel, activated charcoal, coconut fiber) and a digital sensor module to measure water quality parameters such as pH, TDS, BOD, COD, DO, and heavy metals. The test results showed that the system was able to reduce BOD levels by up to 80%, COD by up to 77%, as well as increase DO and neutralize pH. The sensor system provides real-time monitoring with high accuracy. These results show that the technology developed is effective, cost-effective, and applicable for small-scale wastewater treatment. This research also supports the implementation of green technology and sustainable water management.

Keywords: biodegradation, smart sensors, microorganisms, liquid waste, processing efficiency

A. Introduction

Clean water is a basic necessity for human survival. However, as urbanization and industrialization increase, water quality is increasingly threatened by liquid waste being dumped into the environment without adequate treatment. Data from the World Health Organization (WHO) shows that more than two billion people in the world use sewage-contaminated water sources, which cause about 485,000 deaths from diarrheal diseases every year. The main pollutants in wastewater often include Volatile Organic Compounds (VOCs), heavy metals, and other hazardous chemicals from the textile, pharmaceutical, food, and agricultural industries.

Wastewater treatment is an important issue globally, especially in the context of environmental sustainability and public health. Conventional treatment technologies such as coagulation, chemical precipitation, and membrane filtration have indeed been widely used, but their effectiveness in addressing complex and toxic pollutants such as lead, arsenic, or phenol is still questionable. In addition, high operational costs, periodic maintenance requirements, and large energy consumption make this conventional method unfriendly to developing countries that have limited resources (Patel & Parmar, 2021; Zhang et al., 2023).

In Indonesia, the challenges of wastewater management have become increasingly complex with population growth and small industrial estates that have mushroomed in various regions. Unfortunately, many of these areas do not have effective wastewater treatment systems. Based on a report from the Ministry of Environment and Forestry (MoEF), more than 70% of rivers in Indonesia are heavily polluted, mostly caused by domestic waste and small industries. Not only that, limitations in real-time water quality monitoring systems are a significant obstacle in anticipating the impact of pollution quickly and accurately (Hydroleap, 2023).

In responding to these challenges, various technological innovations have been developed. One of the rapidly developing approaches is the use of biofiltration, which is a water purification technique by utilizing microorganisms that live on a specific medium (e.g. activated charcoal, coconut coir, or sand) to decompose organic and inorganic pollutants. Research by Wang et al. (2020) shows that microbe-based biofilters are able to reduce the levels of BOD, COD, and heavy metals with an efficiency of more than 85%. Meanwhile, along with the development of digital technology, smart sensors based on the Internet of Things (IoT) have also been widely used to detect water quality parameters such as pH, temperature, TDS, and heavy metal concentrations in real-time (Khan et al., 2022).

However, there is still little research that integrates biofiltration systems and smart sensor technology in one comprehensive and sustainable treatment system. Most previous studies have focused only on the development of conventional biofiltration without the support of automated monitoring, or conversely, only developing monitoring systems without an active biological treatment system. Therefore, this study focuses on the development of an integrated system that combines the effectiveness of biofiltration in decomposing pollutants with the reliability of smart sensors in monitoring water parameters directly.

The urgency of this research is very high, considering that Indonesia still urgently needs wastewater treatment technology that is efficient, cheap, and easy to apply on a small and medium scale. In addition, with the integration of digital technology, the wastewater treatment process can be carried out automatically, efficiently, and data-based. This will help local governments, small industries, and communities manage waste independently without relying on expensive and complex centralisation systems.

The novelty of this research lies in the integration of two technological systems: biofiltration as a processing system and smart sensors as a monitoring system. These two technologies are connected in a single prototype unit that can operate automatically. This prototype is not only capable of treating wastewater, but also actively detects and informs water quality in real-time through digital devices, which can be accessed through an online dashboard or smartphone-based application. The innovation of this study lies in the seamless integration of biofiltration and IoT-enabled real-time monitoring, which addresses both treatment efficiency and monitoring gaps simultaneously—an approach not widely applied in prior studies

This research aims to develop a prototype of a biofiltration-based wastewater treatment system equipped with smart sensors for real-time monitoring of water quality. In addition, this study also aims to test the effectiveness of the system in reducing the levels of major pollutants such as BOD, COD, TSS, pH, and heavy metals. Finally, another goal is to evaluate the accuracy of the sensors in detecting changes in water quality directly as well as an analysis of the energy efficiency and cost of the system.

In terms of benefits, this research is expected to make a significant contribution in several aspects. Academically, this research adds to the wealth of science about the integration of biotechnology-based water treatment systems and digital technology. Technologically, this research will produce a prototype of a tool that can be adapted and modified according to local needs. From a social and environmental perspective, this research will help reduce water pollution and the risk of diseases caused by liquid waste. Meanwhile, economically, this system will be a cost-effective solution and can be used by small-scale industry players and village communities.

The implications of this study are also quite broad. First, the results of the research can be a reference for the government in formulating wastewater management policies based on green technology. Second, this system can be adapted by the industrial sector to improve the efficiency of the waste treatment process. Third, this system also opens up opportunities for the development of water treatment technology that can be controlled remotely and cloud-based.

Thus, this research not only contributes to solving environmental problems locally, but also contributes to the achievement of the Sustainable Development Goals (SDGs), especially point 6 (clean water and sanitation) and point 9 (industry, innovation, and infrastructure). The development of this technology is a concrete step towards sustainable and inclusive management of water resources.

B. Research Method

This research uses a Research and Development (R&D) approach with the main objective of designing, developing, and evaluating a biofiltration-based wastewater treatment system integrated with smart sensor technology. The R&D method was selected due to its structured steps that support iterative prototyping, testing, and refinement—suitable for engineering applied technology systems with both biological and digital components. This approach was chosen because the main focus of the research is to produce applied technology products that are innovative and can be tested directly in real scenarios. The development model used in this study adapts the Borg & Gall model, which is then simplified into five core stages: preliminary study, initial product design, design validation, limited field trials, and product revision and refinement.

In the preliminary study stage, an in-depth literature review was carried out on biofiltration technology and smart sensors in wastewater treatment, as well as the collection of empirical information on the characteristics of domestic and small industrial wastewater at the research site. The results of this stage are used as a basis for designing the initial prototype system. This initial design was then validated by experts in the field of environmental engineering and sensor technology to ensure technical and functional feasibility.

The developed processing system consists of two main components. The first component is the biofilter, which serves as a biological system for filtering and decomposing pollutants in wastewater. The biofilter is designed in the form of a vertical tube with three layers of media, namely coarse gravel at the bottom, activated charcoal in the middle, and coconut coir at the top. Each medium was chosen for its ability to support the growth of decomposing microorganisms and its effectiveness in absorbing organic and inorganic matter. The process of water treatment through biofiltration relies on the mechanism of biodegradation by microbes as well as the adsorption of harmful substances on the surface of the filtration media.

The second component is a smart sensor that plays a role in monitoring water quality in real-time during the process. The sensors used include pH, temperature, Total Dissolved Solids (TDS), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), as well as heavy metal content such as Pb, Cd, and Cr. All sensors are integrated in a single microcontroller-based system (using Arduino or ESP32) and connected to a web-based digital platform or mobile application. This allows for live remote monitoring through an informative user interface.

The research was conducted in two locations, namely the environmental engineering laboratory for the initial assembly and testing process, and the field location which is a small household industry (such as laundry units and tempe-tofu industry) in urban/sub-urban areas. This location was chosen purposively because it produces liquid waste that contains high organic substances, making it suitable for testing the effectiveness of the developed system.

The wastewater samples used consisted of two types, namely raw wastewater and treated water from the prototype system. The water quality parameters tested included pH, TDS, BOD, COD, Dissolved Oxygen (DO), and heavy metal content. Sampling was carried out for three consecutive days with three repeats of the test per type of water to ensure the validity of the results.

Data collection is carried out through various techniques. Digital sensors are used to measure water parameters directly and automatically. Meanwhile, laboratory testing was carried out to ensure the accuracy of measurement results, especially for BOD, COD, and heavy metal parameters, using spectrophotometry and titration. Technical observations are also carried out to record the overall performance of the system, such as the duration of filtration time, media saturation, and sensor response to changes in water conditions. Visual documentation in the form of photos, schematics, and videos is also carried out to support the preparation of reports and the presentation of data.

The instruments used in this study were first tested for validity and reliability. Validation is carried out through a comparative test of sensor reading results with laboratory tests, while reliability is tested by repeating measurements under the same conditions to ensure data stability and consistency.

The data obtained was then analyzed descriptively quantitatively. The analysis of the effectiveness of biofiltration was carried out by comparing the initial and final values of the water quality parameters. The percentage decrease in pollutant concentration is calculated as an indicator of the success of the system. In addition, sensor performance was analyzed by looking at the error margin between sensor data and laboratory results. The overall evaluation of the product is also carried out based on the efficiency of processing time, ease of use, and potential application on a community or small industry scale.

With this methodological approach, the research is expected not only to produce valid and reliable empirical data, but also to be able to produce applied technology products that are ready to be implemented in a real context, especially as an efficient, economical, and sustainable liquid waste treatment solution.

C. Result and Discussion

This research resulted in a prototype wastewater treatment system that integrates biofiltration technology with an Internet of Things (IoT)-based smart sensor system. The prototype was tested experimentally to measure its ability to reduce the level of major pollutants in domestic wastewater, which comes from small and medium-sized enterprises (SMEs) such as the tofu-tempeh industry and home laundry.

1. General Description of Prototype

The prototype consists of a three-layer vertical biofilter with gravel media, activated charcoal, and coconut fiber. Each layer plays a role in reducing solutes and improving the biochemical conditions of the water. The smart sensors integrated in the system are able to automatically measure six water quality parameters and transmit data in real-time to a web-based dashboard.

The sensors used include pH, TDS (Total Dissolved Solids), DO (Dissolved Oxygen) sensors, as well as sensors for BOD, COD, and heavy metals (Pb). Measurements were taken before and after the processing process, for three consecutive days.

2. Wastewater Quality Test Results

The following table presents the average results of wastewater quality measurements before and after treatment:

Table 1. Wastewater Quality Test Results

Parameters	Before Processing	After Processing
Ph	5.4	7.1
TDS (mg/L)	950	310
BOD (mg/L)	180	35
COD (mg/L)	400	90
DO (mg/L)	1.8	5.4
Pb (mg/L)	0.15	0.03

3. Interpretation and Effectiveness

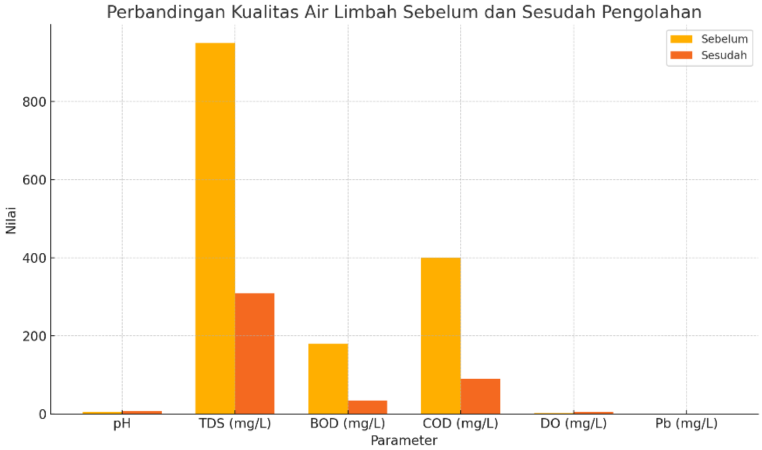
The test results showed a significant improvement in post-treatment wastewater quality. The pH parameter has improved from acidic (5.4) to neutral (7.1), which indicates that the biofiltration process can stabilize the acidity level of the water. Total Dissolved Solids (TDS) decreased drastically from 950 mg/L to 310 mg/L, demonstrating the ability of filtration media to absorb solutes.

Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), two main indicators of organic pollution, decreased by 80.6% and 77.5%, respectively. This shows that the activity of microorganisms in the biofiltration medium is very effective in decomposing the organic matter contained in the wastewater.

Dissolved Oxygen (DO) levels increased from 1.8 mg/L to 5.4 mg/L, indicating that the treated water is becoming richer in oxygen and more friendly to aquatic life. Meanwhile, heavy metal levels of Pb also decreased significantly from 0.15 mg/L to only 0.03 mg/L, close to the safe threshold set in Government Regulation No. 82 of 2001 concerning Water Quality Management.

4. Visualization of Results

The following graph illustrates a comparison of wastewater quality parameters before and after treatment, which further confirms the effectiveness of the developed system:



This graph shows that all parameters are changing for the better, with the highest rates of decline occurring in BOD and COD. This signifies that the biofiltration system is highly effective in addressing organic pollutants, while smart sensors provide the convenience of monitoring results directly.

5. Smart Sensor Performance

During the test, the sensor system showed high accuracy, with a margin of error of no more than ±5% compared to the laboratory test results. The pH and DO measurements show constant stability of values in both digital and manual systems. In addition, the data transmission system works in real-time, with a transmission delay of under 2 seconds.

The designed dashboard also makes it easier for users to read information, set threshold alarms, and save daily data history. This feature is especially useful for continuous monitoring by small industries or communities with limited technical resources.

Research Discussion

This research aims to develop and test a biofiltration-based wastewater treatment system integrated with smart sensor technology. The results of the test show that this system is able to significantly improve wastewater quality, both from physical, chemical, and biological aspects. This discussion will focus on the interpretation of the results, analysis of the effectiveness of the system, validation through sensor data, as well as comparison with previous research and its potential practical implications.

1. Effectiveness of Biofiltration in Wastewater Treatment

One of the main findings of this study is the success of the biofiltration system in lowering the levels of major pollutants, such as BOD, COD, TDS, and heavy metals. A decrease in BOD from 180 mg/L to 35 mg/L suggests that microorganisms in a biofilter medium can actively decompose complex organic compounds into simpler, harmless compounds. A decrease in COD from 400 mg/L to 90 mg/L indicates that the system is able to remove oxidized chemicals that are usually difficult for conventional systems to decompose. This effectiveness is in line with the findings of Wang et al. (2020), who reported that biofilters with active media and selective microbes can lower COD by more than 75% in a filtration time of 4–5 hours.

In addition, the reduction of TDS from 950 mg/L to 310 mg/L indicates that the filtration medium is able to absorb solutes such as salts, detergent residues, or other chemical compounds that generally come from household and small industrial waste. These findings are in line with a study by Maurya & Sharma (2020) which showed that the use of activated charcoal and coconut fiber can increase adsorption capacity by up to 60% compared to ordinary sand media. These materials were chosen due to their proven adsorption properties, high surface area, and biocompatibility with microbial colonies involved in biodegradation (Maurya & Sharma, 2020

The pH level of 5.4 (acidic) increased to 7.1 (neutral), indicating that the system is able to stabilize chemical reactions in wastewater. The pH balance is essential to maintain aquatic life as well as avoid corrosion in sewers. The increase in Dissolved Oxygen (DO) from 1.8 mg/L to 5.4 mg/L is also an indicator that the treated water contains enough dissolved oxygen, making it suitable for release into the environment or reused for non-consumption technical purposes.

2. The Role of Smart Sensors in Real-Time Monitoring

Smart sensors integrated into the system prove to be very helpful in monitoring water quality parameters. With pH, TDS, DO, sensors and electrochemical-based heavy metal detectors, users can directly know the status of wastewater, both before and after treatment. This system allows for early detection of changes in water conditions, such as spikes in TDS due to detergent contamination or pH drops due to acid chemical residues.

The sensor works in a real-time system that connects to the ESP32 microcontroller and is displayed via a web-based dashboard. Users can simply access the app through a mobile device or computer to view the graphical parameters over time. This advantage provides flexibility and efficiency that is not widely available in conventional wastewater treatment systems, which often rely only on periodic laboratory tests.

The sensor performance also shows valid and stable results, with a measurement error rate below 5% when compared to laboratory results data. These findings support the results of Khan et al.'s (2022) research, which states that IoT-based sensor systems have high accuracy for water quality monitoring applications, and can be a decision support system for waste treatment operators.

3. System Advantages and Innovation

The system developed in this study not only offers a solution to water pollution, but also represents an environmentally friendly technological approach that is feasible to be applied in areas with minimal infrastructure. The advantages of this system lie in the aspects of cost efficiency, ease of maintenance, and automatic monitoring capabilities that traditional wastewater treatment technology does not have.

The main innovation of this research is the integration between biological systems (biofiltration) and digital technology (smart sensors). This approach combines two fields of science: environmental engineering and information technology. This system is suitable for large-scale households, small-medium industries, and village communities that need independent wastewater treatment without central infrastructure.

4. Comparison with Previous Research

When compared to similar research, this system shows advantages in terms of technological integration. For example, Patel et al. (2021) developed a high-efficiency biofiltration system, but it is not integrated with an automated monitoring system. On the other hand, the study of Zhang et al. (2023) developed smart sensors to detect heavy metals in water, but did not associate such data with active waste treatment systems.

Thus, this study complements the shortcomings of the previous two approaches and presents a complete solution model—from simultaneous processing to monitoring. In addition, the added value of this integration lies in the collection of historical data that can be used for pollution trend analysis and long-term planning.

5. Practical Implications and Sustainability

In practical terms, this system can be applied on a community scale to efficiently treat domestic waste. In the context of sustainable environmental management, these systems can reduce dependence on centralized treatment systems and increase community participation in maintaining water quality.

One important implication is the potential of this system to support the **Sustainable Development Goals (SDGs),** in particular point 6 (clean water and sanitation) and point 9 (innovation and infrastructure). In the long term, this system can also be further developed to support *an early warning system* against river or groundwater pollution.

6. Research Limitations

Although the results show the effectiveness of the system, there are still some limitations. First, the prototype is still laboratory scale and semi-manual. In widespread application, it is necessary to develop systems that are more resistant to extreme environmental conditions such as temperature fluctuations and water discharge. Second, the heavy metal sensors used are still limited to lead (Pb) parameters, so in the future it will need to be developed for other metals such as Cd, Hg, or Cr.

Another limitation is the reliance on an internet connection for IoT-based monitoring systems. In areas with limited internet connections, the sensor's function may not be optimal. Therefore, the system needs to be adapted to be *offline-capable* or use local data storage.

D. Conclusion

This research has succeeded in developing a wastewater treatment system that integrates biofiltration technology with smart sensors based on the Internet of Things (IoT). The test results show that this system is effective in lowering the levels of major pollutants in wastewater, such as BOD, COD, TDS, and heavy metals, while improving the quality of pH and DO to reach disposable water quality standards. The biofiltration process is proven to be able to efficiently decompose organic matter through structured biological media, while smart sensors provide accurate real-time monitoring of water quality parameters.

The main advantage of this system is its ability to operate automatically and provide data that can be accessed directly by users through a digital dashboard. These findings show that this system has great potential to be applied at the scale of households, communities, and small industries that do not yet have access to centralized waste treatment systems. This research not only provides solutions to water pollution, but also paves the way for the development of efficient, environmentally friendly, and digital-based waste treatment technology in a sustainable manner. Future development should explore rugged casing materials for outdoor deployment and integrate additional offline storage modules to mitigate dependence on continuous internet connectivity.

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