SIPANDU: An IoT-Based Integrated River Waste Monitoring and Collection System Powered by Solar Energy

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Abstract: River pollution caused by waste accumulation, especially plastic waste, has become a significant environmental problem in urban areas. Rivers act as transportation routes that carry waste from land to sea and contribute to global plastic pollution. Various Internet of Things (IoT)-based water quality monitoring systems have been developed to monitor environmental conditions in real time. However, most existing research still focuses on monitoring environmental parameters without integrating with automatic waste transport mechanisms or independent energy sources, which limits the effectiveness of the system, especially in river locations far from electricity sources. This study proposes SIPANDU (Integrated River Waste Monitoring System), an IoT-based system that integrates direct river condition monitoring, waste transport mechanisms using automatic conveyors, and the use of renewable energy through solar power plants. This system consists of a 100 Wp solar panel, a battery for energy storage, water quality sensors (pH and TDS), an ultrasonic sensor to detect the presence of waste, and a web-based monitoring platform for real-time data visualization.

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The test results show that the solar panels produce a maximum power of 61.1 W with an average power of around 41.87 W. The conveyor system is capable of transporting up to 5 kg of waste with an average power consumption of 33.43 W. The integration of the IoT system, renewable energy, and automatic waste transportation shows that SIPANDU can function as a river monitoring system as well as a sustainable technology solution for waste management in rivers.

Keywords: SIPANDU, IoT System, Solar Power System, Automatic Conveyor, Monitoring System

Introduction

River pollution due to the accumulation of waste, particularly plastic, has become a global environmental issue in recent years. Rivers serve as transport routes for waste to the ocean and contribute significantly to plastic pollution in marine ecosystems (Lebreton et al., 2017). As plastic waste accumulates in waterways, it is clear that plastic pollution can pose a threat to the environment (van Emmerik & Schwarz, 2020). In addition to large-sized waste, microplastic particles are also harmful to the environment. These small particles can accumulate in the bodies of aquatic animals and enter the food chain, ultimately being consumed by humans (Wagner et al., 2014). This issue demonstrates that river management requires not only water quality monitoring systems but also technology that can handle waste directly and sustainably.

To support more effective river management, Internet of Things (IoT) based environmental monitoring technology is beginning to be widely developed. This system enables the automatic, real-time collection of water quality data through a network of connected sensors. (Georgantas et al., 2025) developed a low-cost water quality monitoring system integrated through a LoRa network, demonstrating the use of sensors and wireless communication for efficient environmental monitoring. (Chowdury et al., 2019) proposed an IoT-based real-time river water quality monitoring system that integrates physical and chemical water sensors with IoT technology to provide direct data access and visualization via a server, including an automatic alert mechanism when parameters exceed thresholds. (Geetha & Gouthami, 2016) presented research and a prototype of an IoT-based water quality monitoring system that emphasizes power efficiency, easy data integration to the cloud, and remote notification when water quality deviates from standards. More broadly, (Zanella et al., 2014) and (Perera et al., 2014) explained that IoT systems in the context of smart cities and environmental monitoring can provide adaptive, contextual, and integrated systems.

In the broader context of water resource management, the integration of digital technology through the Internet of Things (IoT) is also being used to support intelligent water

management systems. The use of smart sensors and real-time data communication has been proposed to improve the accuracy of water quality monitoring (Lakshmikantha et al., 2021). Another study by (Tedjojuwono & Jahja, 2024) demonstrated the implementation of an IoT sensor-based water management system to measure water and flow parameters, integrated with a data platform to improve technical measurement processes and interoperability between devices. Analysis of IoT-based water monitoring systems in a literature review (Zulkifli et al., 2022) demonstrated that this technology plays a role in collecting water quality data to support more responsive and informative resource management planning. Furthermore, a review of IoT and artificial intelligence technologies indicates that the combination of IoT, cloud data processing, and predictive models can expand applications for monitoring and managing wastewater and clean water networks (Alprol et al., 2024).

In addition to monitoring and data management, the operational sustainability of environmental monitoring systems is also significantly influenced by the availability of energy sources. In many field monitoring applications, such as rivers or remote areas, the use of renewable energy is a solution to support autonomous system operations. Several studies have integrated IoT technology with renewable energy systems to support sustainable environmental monitoring. A study by (Shukla et al., 2026) discusses the integration of IoT in photovoltaic (PV) systems for real-time performance monitoring and energy efficiency optimization through cloud-based architecture and edge computing. Other studies by (Stoica et al., 2025) and (Rouibah et al., 2025) demonstrate the implementation of IoT-based smart sensors to improve the monitoring accuracy and efficiency of renewable energy systems. The development of smart sensor devices with IoT connectivity for real-time monitoring of physical and chemical parameters is discussed by (Wiryasaputra et al., 2024), which demonstrates the importance of sustainable data acquisition systems in mitigating environmental risks. In the context of the water-energy nexus, (Aderemi et al., 2025) explore the integration of smart monitoring technologies to improve the efficiency of water-based systems. A technical analysis and system modeling approach for optimizing monitoring devices is discussed in the journal (Muhammad Iqbal, 2023), while an evaluation of the implementation of applied engineering technology to improve environmental system performance is presented in the journal (Yosi Apriani et al., 2023).

Although various studies have developed IoT-based water quality monitoring systems, most of these studies still focus on monitoring environmental parameters without integrating waste management systems directly into the water. Furthermore, some monitoring systems still rely on external energy sources, making them less than optimal for applications in remote rivers. Therefore, a system is needed that not only monitors river environmental conditions in real time but also automatically handles waste with the support of an independent energy source.

Based on these issues, this study proposes SIPANDU (Integrated River Waste Monitoring System), which integrates Internet of Things technology, an automatic conveyor system for waste transportation, water quality sensors, and a solar panel-based renewable energy source into a single operational system. Unlike previous studies, which generally focused solely on environmental monitoring, SIPANDU is designed as a system capable of monitoring river conditions in real time while also automatically transporting waste. Furthermore, SIPANDU is equipped with a website-based monitoring platform for directly monitoring river conditions, and the use of solar energy makes SIPANDU an energy-independent system that can be implemented in various river locations without dependence on an external electricity grid.

Research Method

Mechanical System Design

SIPANDU is designed as a system that integrates energy, control, mechanics, sensors, and IoT into a single operation. The mechanical structure of SIPANDU is designed to operate stably in aquatic environments such as rivers. The main components of this design include: 1) The main frame of the device is made of sturdy material to support all components, including solar panels, 2) Cylindrical floats so that the device can float and follow fluctuations in river water levels, 3) A conveyor system as a waste transport mechanism using a belt conveyor that is installed at an angle to reach the water surface, 4) A storage container or tank used to collect waste that the conveyor has lifted. SIPANDU is designed with main dimensions of approximately 94 cm long, 68 cm wide, and 127 cm high. The main frame of the tool is made of iron material, which functions as a supporting structure for all components. Solar panels are placed on the top of the frame with dimensions of approximately 94 cm × 68 cm to maximize solar energy absorption. The conveyor system has a length of approximately 100 cm with an inclination angle of approximately 50° to facilitate the process of transporting waste from the water surface to the collection container. In addition, the main frame that supports the system is approximately 115 cm high, while the floating frame used as a tool support has a length of 100 cm to maintain the stability of the tool during use in the water. All components are designed so that SIPANDU can work stably and efficiently in the process of transporting river waste. The complete mechanical system design of SIPANDU can be seen in Figure 1.
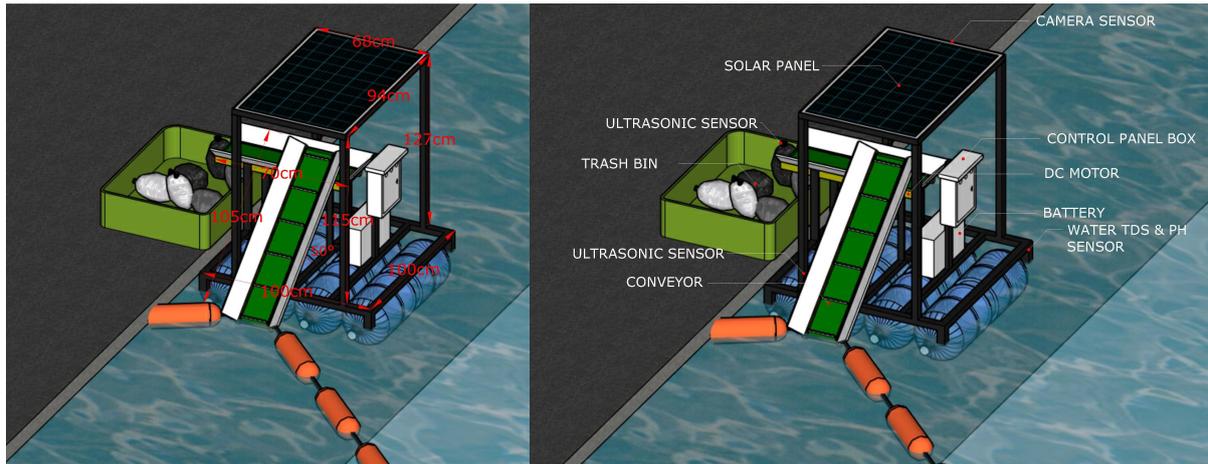
Figure 1 Mechanical Design and Dimensions of the SIPANDU

Solar Energy System Design (PLTS)

As an energy-independent system, the main energy source used is a solar power plant (PLTS). This type of power plant uses solar energy as a renewable energy source, with the main component being solar cells (photovoltaic cells) (Makkulau et al., 2021). The PLTS system consists of a 100 Wp solar panel, a solar charge controller (SCC), and a 12 V battery for energy storage for a certain period. The photovoltaic principle is to convert the photon energy from sunlight into electrical energy (Samsurizal et al., 2020), which is then regulated by the SCC before being stored in the battery to maintain charging voltage stability and prevent battery damage from overcharging (Nugraha et al., 2025). The energy stored in the battery powers all components, including the ESP32 microcontroller, pH sensor, TDS sensor, HC-SR04 ultrasonic sensor, current and voltage sensors, the IoT communication system, and the DC motor that drives the conveyor. The power model of solar panels is expressed by the equation (Hassan et al., 2023):

$$P = V \times I \tag{1}$$

The electrical energy produced by the system can be calculated using the following equation:

$$E = P \times t \tag{2}$$

Where P is power (W), V is voltage (V), I is current (A), and t is operating time (hours). The results of the power and energy calculations are then compared with the solar power system's capacity to evaluate the adequacy of the solar panel's power in supporting SIPANDU's energy needs. The evaluation of the PLTS system's performance is based on the suitability of the solar panel's output power, the stability of the battery charging voltage, and the system's ability to support SIPANDU's operations according to the planned duration. Figure 2 shows the energy flow diagram illustrating the integration of energy sources, energy storage, and system loads.
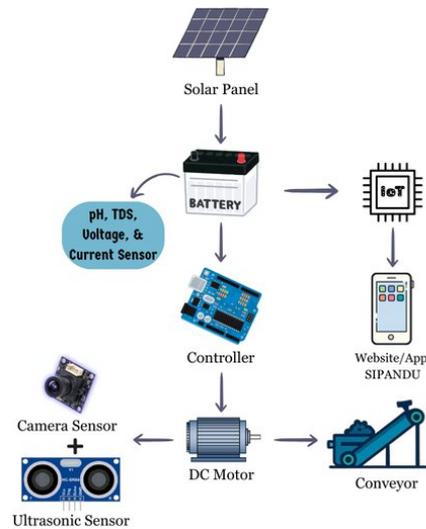
Figure 2 Energy Distribution Flow

Control and Sensor System

The SIPANDU control system and sensors are designed to be integrated with the ESP32 microcontroller as the control center and data processing unit. The configuration of the connections between the control system components, sensors, actuators, and communication modules is shown in Figure 3, which is based on the system wiring diagram.
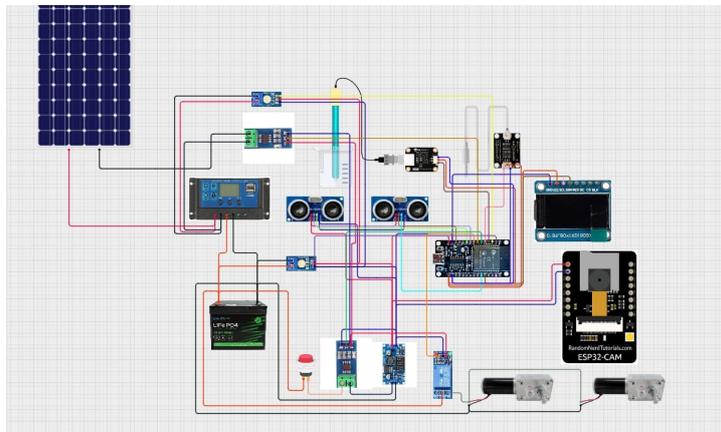

Figure 3 Wiring Diagram System

The sensors in this system consist of pH and TDS sensors that function to monitor river water quality in real time (Chuzaini et al., 2022), current and voltage sensors to monitor the electrical system in real time, and ultrasonic sensors used to detect the presence and volume of waste (Rohman et al., 2018). All sensors are directly connected to the ESP32 as the main processing unit. Data from these sensors is collected, processed, and analyzed digitally to determine environmental conditions and the system's operational status. The specifications of the sensors used in this system, including the sensor type, measurement range, resolution, and calibration process, are shown in Table 1.

Table 1 Specifications of sensors used in the SIPANDU

Sensor	Type	Measurement Range	Resolution	Calibration Process
pH	pH-4502C	pH 0 - 14	± 0.01 pH	Using buffer solutions of pH 4, pH 7, and pH 10
TDS	DFRobot SEN0244	0 – 1000 ppm	± 1 ppm	Using a standard TDS solution
Ultrasonic	HC-SR04 Ultrasonic sensor	0 cm – 400 cm	± 0.3 cm	Compare the sensor reading results with the actual distance using a ruler or meter
Voltage	Voltage sensor / 170640	0 – 25 V	±0.004 V	Sensor to a known voltage source, then the voltage value is measured using a multimeter as a comparison
Current	ACS712 5A	-5 up to +5 A	± 0.01 A	Connect the sensor in series with an electrical load. Measure the current flowing using a multimeter as a reference

The ESP32 functions as a central control unit that processes sensor data and generates control signals to actuators (Muliadi et al., 2020). Based on the processed data, the ESP32 controls the relay module to regulate the power supply to the DC motor that drives the conveyor system. This mechanism allows the system to transport waste based on the detected environmental conditions automatically. In addition to its control functions, the system includes a monitoring and data visualization interface. System information is displayed on an OLED screen as a local interface, while environmental data and system status are sent to an IoT platform for remote monitoring. The ESP32-CAM module is used as a visual monitoring system that provides a real-time view of river environmental conditions. This configuration forms a closed-loop system in which environmental detection, data processing, decision making, and mechanical responses occur automatically and continuously. The integration of sensors, controllers, actuators, and monitoring systems makes SIPANDU an intelligent system that is adaptive to changing environmental conditions.

Software Architecture

The system's working logic is designed using flowcharts to ensure that each monitoring and control process runs in the correct sequence. The system workflow is shown in Figure 4 below.
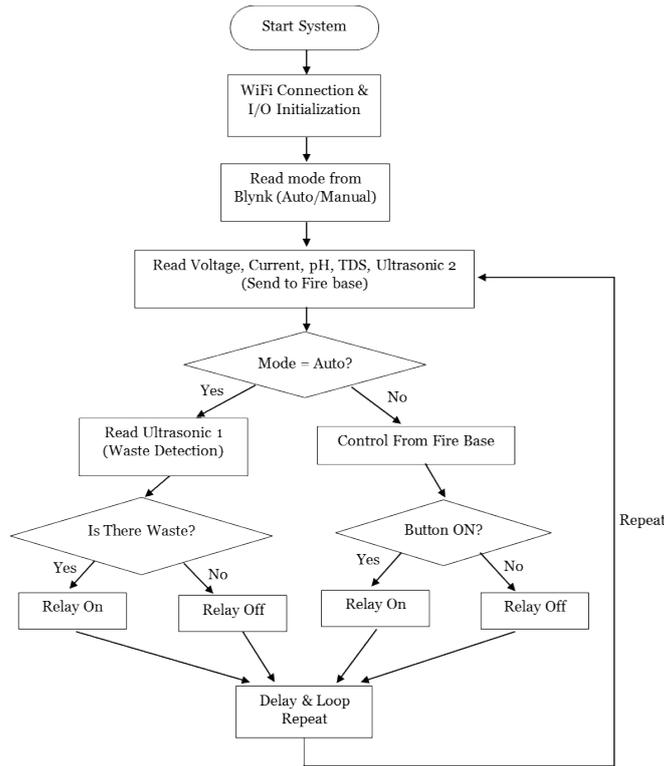
Figure 4 Flowchart System

Result and Discussion

Performance Characteristics of the PLTS System

Solar panel performance testing was conducted to evaluate the panel's ability to generate electrical power as the main source for SIPANDU operations. The 100 Wp solar panel was tested by measuring the voltage and current output at specific time intervals starting at 9:00 AM WIB to 1:30 PM WIB to represent the variation in solar intensity from morning to afternoon. The weather conditions during the test were relatively clear with few clouds in the morning and towards the afternoon. Voltage and current data were collected periodically every 30 minutes using sensors integrated with the ESP32 system. The variation in output power obtained was influenced by changes in solar radiation intensity during the test period.

Table 2 PLTS Data System

Parameter	Value
Minimum Power	29.6 W
Maximum Power	61.1 W
Average Power	41.87 W
Peak Time	11:30 AM – 12:00 PM
Average Voltage	16.35 V
Average Current	2.62 A

Based on Table 2, the average output voltage was 16.35 V, while the average output current was around 2.62 A. The panel's output power was calculated using equation (1), resulting in a maximum of 61.1 Watts at 12:00 p.m., after which it gradually decreased. These test results show that the solar panel's output power fluctuates with the sun's intensity. Figure 5 below shows the power time graph. Theoretically, solar panels rarely produce peak power according to their nominal capacity due to non-ideal factors, such as light intensity, solar panel temperature, and system losses (Ady Pratama & Herlamba Siregar, 2018). The test results align with this theory: the 100 Wp solar panel can only deliver ±61% of its nominal capacity. Nevertheless, the average power generated by the solar power system is still sufficient to support the continuous operation of the IoT-based monitoring system, sensors, and control system. These results show that weather conditions and solar radiation intensity have a direct influence on fluctuations in solar panel output power.
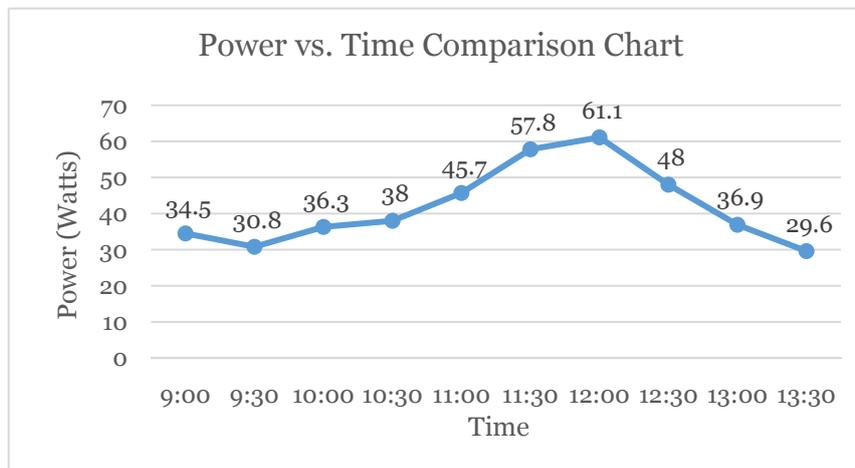

Figure 5 Power vs. Time Graph

Energy Budget Analysis

In order to evaluate the energy adequacy of the system, an energy balance analysis was conducted by comparing the daily energy generated by the solar panels to the total energy consumption of the system load, including IoT monitoring and conveyor motors.

Table 3 Energy Budget Analysis of the SIPANDU

Parameter	Value
Solar panel capacity	100 Wp
Estimated PV Energy yield	340 Wh/day
IoT monitoring system load	88 Wh/day
Conveyor motor load	864 Wh/day
Total energy consumption	952 Wh/day
Battery capacity	1200 Wh
Effective battery capacity (DoD 80%)	960 Wh

Based on the energy balance analysis shown in Table 3, a 100 Wp solar panel is estimated to produce approximately 340 Wh/day of energy, assuming an effective irradiation duration of approximately 4 hours per day and a system efficiency of approximately 85%. SIPANDU's energy consumption, consisting of sensors, IoT monitoring, and conveyor motors, is estimated at 952 Wh/day. This energy is supplied by a 1200 Wh lithium battery with an effective capacity of approximately 960 Wh at a depth of discharge (DoD) of 80%. System efficiency is also influenced by the efficiency of the solar charge controller (SCC) and the efficiency of the battery charging process, which is generally in the range of 90–95%. However, SIPANDU's conveyor motors do not operate continuously; they are only activated when sensors detect the presence of waste nearby. Therefore, the actual system energy consumption may be lower than the maximum estimate shown in the energy balance analysis.

Automatic Conveyor Performance

Conveyor performance testing was conducted by applying varying waste loads to the conveyor system to determine the relationship between load mass and DC motor power requirements. Based on the results in Table 4, the system was capable of transporting loads of up to 5 kg with a maximum power of 44.8 W and an average power of 33.43 W.

Table 4 Conveyor Performance Data

Parameters	Value
Minimum Load	0 kg
Maximum Load	5 kg
Minimum Power	22.01 W
Maximum Power	44.8 W
Average Power	33.43 W

An increase in waste load shows a linear relationship with an increase in DC motor power, as shown in Figure 6, reflecting the working characteristics of the mechanical conveyor system. At minimum load, the required power is relatively small, while at maximum load it increases significantly due to the higher torque required to drive the conveyor.
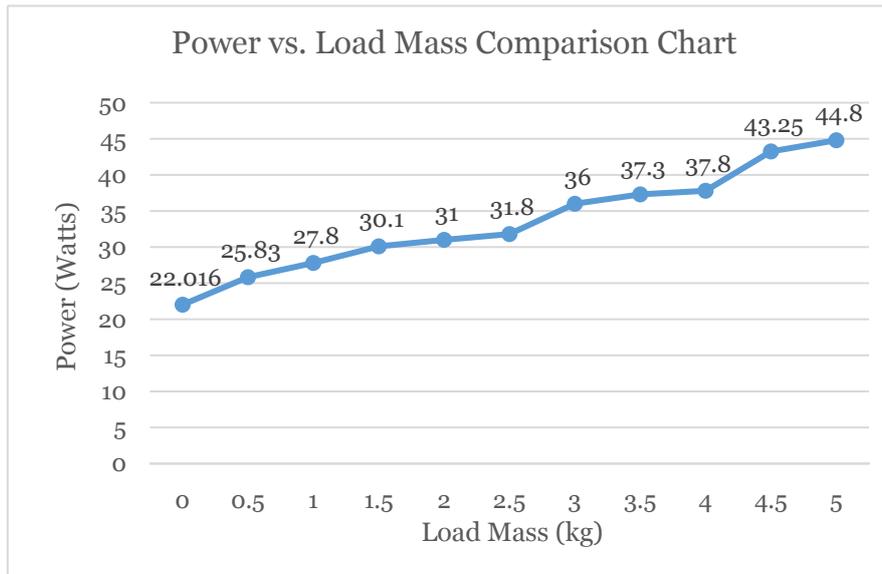
Power vs. Load Mass Comparison Chart

Figure 6 Power vs. Load Mass Graph

Compared with the average solar panel output power of 41.86 W, the conveyor's power requirement of 33.43 W indicates that, in terms of energy, the system remains within the operational limits supplied by the solar power system via a battery energy storage mechanism. This confirms that SIPANDU is not designed as a direct supply system from solar panels to motors, but rather as a battery-based system in which batteries serve as an energy buffer to maintain the operational stability of mechanical loads.This configuration shows that the SIPANDU design uses an energy-storage-based independent energy system, which is better suited to field applications that depend on renewable energy sources.

Remote Monitoring

The SIPANDU remote monitoring system is implemented via an application and a website, integrated with the ESP32 module. This system enables real-time monitoring of environmental conditions and equipment operational status. The Real-Time Data feature displays pH, TDS, current, voltage, and waste volume percentage for the storage tank, along with controllable mode and relay status. This feature allows operators to monitor conditions and retrieve system data without being on site.

Figure 7 Real-time monitoring interface of SIPANDU

The Data History feature displays pH, TDS, Current, Voltage, and waste volume data records on specific dates and times, enabling periodic analysis of trends in water quality and waste conditions.
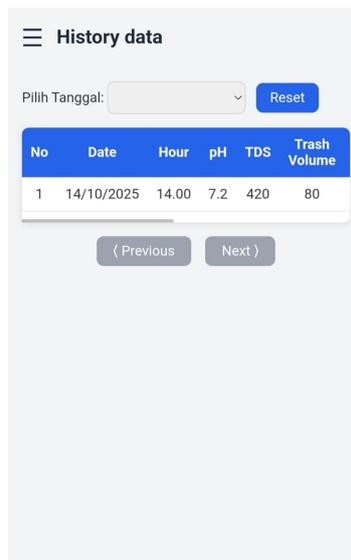

Figure 8 Data history interface

The Camera feature visually displays the river's condition as a field monitoring system, while the Camera History serves as visual documentation for operational analysis and evaluation.
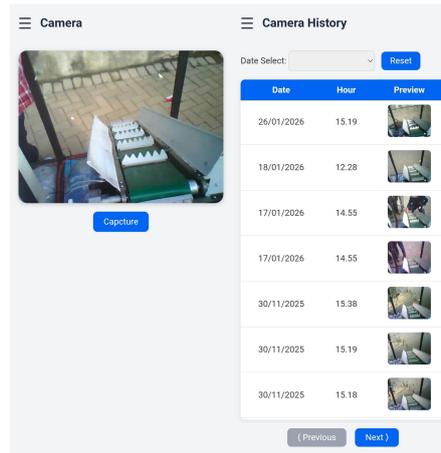
Figure 9 Real-time visual monitoring and Camera history interface

The integration of these features makes SIPANDU an IoT-based smart monitoring system that not only functions as an automatic waste-cleaning tool, but also as a data and visually based river environment monitoring system that supports real-time decision-making.

Conclusions

Based on the results of the design, testing, and analysis that have been carried out, SIPANDU has been successfully developed as an Internet of Things (IoT)-based river waste monitoring and transportation system supported by renewable energy sources in the form of solar panels. This system integrates a 100 Wp solar power generator, a battery as energy storage, an automatic conveyor, sensors, and a digital monitoring system in one interconnected working system. The test results show that the solar panel produces a maximum power of 61.1 W with an average power of 41.87 W, which can support the operation of the monitoring system and conveyor through an energy storage mechanism in the battery. The conveyor system can transport waste loads of up to 5 kg with an average power requirement of 33.43 W. The integration of the IoT monitoring system, water quality sensors, and renewable energy systems shows that SIPANDU not only functions as a real-time river condition monitoring platform but also as an automatic waste transportation tool. However, this research still has limitations on the prototype scale and relatively limited testing duration. Further research could focus on long-term testing in real river environments as well as optimizing solar energy systems to improve system efficiency and reliability.

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