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Posted Date: 7 May 2026

doi: 10.20944/preprints202605.0423.v1

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Article

Integrated Solar-Powered Clean Water Treatment System for Smart Building: A Case Study on Sustainable Technology and Building Deployment in the Remote Region

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Abstract

Limited access to clean water and reliable electricity infrastructure remains a major challenge in many remote regions of Indonesia, particularly for building-scale domestic use. Conventional water treatment systems are often constrained by high operational costs and dependence on grid power, highlighting the need for sustainable and autonomous infrastructure solutions. This study presents the design, development, and performance evaluation of an integrated solar-powered clean water treatment system for smart building applications in remote areas using a Research and Development (R&D) approach. The proposed system combines off-grid polycrystalline photovoltaic panels with a multi-stage water treatment process consisting of a floss (mud) filter, activated carbon filter, water hyacinth cellulose bio-filter, ultraviolet (UV) sterilization unit, storage tank, and an IoT-based real-time water quality monitoring system. System performance was evaluated through microbiological, physical, and chemical water quality testing, with monitoring conducted via Wi-Fi-enabled sensors connected to the Blynk platform. The results demonstrate substantial improvements in treated water quality. *Escherichia coli* and total coliform bacteria were eliminated (100% reduction). Total dissolved solids (TDS) decreased from 450 mg/L to 218 mg/L (51.6%), and dissolved manganese was reduced from 30 mg/L to 0.01 mg/L (99.97%), while nitrate levels decreased by 50%. Water pH and temperature remained stable and within regulatory limits. All treated water parameters complied with national clean water standards for hygiene and sanitation. The system operated independently using solar energy and achieved a clean water production capacity of 1,000–1,500 L/day. These findings indicate that the proposed system is a feasible, cost-effective, and sustainable civil engineering solution for clean water infrastructure in remote building environments.

Keywords: clean water treatment; IoT monitoring; remote areas; renewable energy; smart building; solar panel; water filtration

1. Introduction

The availability of clean water is a fundamental requirement for human life, yet it remains a serious challenge in many remote regions of Indonesia [1–2]. According to data from the Ministry of Health, approximately 30 percent of the population living in remote areas still has trouble accessing clean water suitable for consumption [3]. Difficult geographical conditions, limited electricity infrastructure, and high operational costs represent major obstacles to the provision of conventional water treatment systems [4–5].

These challenges are further compounded by increasing levels of water source contamination caused by human activities and climate change [6–8]. The impacts extend beyond public health concerns, also hindering economic and social development in affected regions [9–10]. Therefore, innovative solutions are required that can comprehensively address these multidimensional problems by integrating water treatment technologies with autonomous, sustainable renewable energy sources.

Advancements in solar cell or photovoltaic panel technology over the past decade have created significant opportunities for the provision of alternative electrical energy that is environmentally friendly and cost-effective [11–12]. The efficiency of modern solar panels has reached 20–22 percent while costs continue to decline, making solar energy an increasingly feasible solution for applications in remote areas [13–15]. As a tropical country, Indonesia possesses abundant solar energy potential, with average solar radiation of approximately 4.8 kWh per square meter per day [16–17].

The integration of solar cell technology with clean water treatment systems offers a synergistic solution [18–19], whereby solar energy can be converted to power water pumps, filtration systems, and sterilization units independently, without reliance on the national electricity grid. This approach aligns with the smart building concept, which emphasizes optimization of natural resource utilization, reduction of carbon footprints, and improvement of operational efficiency.

This study aims to design and construct an integrated solar-powered clean water treatment system that can be applied to smart buildings in remote areas. The system design integrates multiple components, including a pre-treatment unit for initial filtration, a multi-stage filtration system, an ultraviolet disinfection unit, storage tanks, and solar panels with capacities tailored to operational requirements. The system is also equipped with sensor technology and real-time monitoring to control output water quality, energy efficiency, and overall operational performance.

The benefits of this research encompass technical, economic, social, and environmental aspects that are significant for the development of sustainable clean water infrastructure in Indonesia. Environmental benefits include reduced carbon emissions and promotion of renewable energy use. Furthermore, this study supports the achievement of the Sustainable Development Goals, particularly universal access to clean water and affordable clean energy, and provides a sustainable technology implementation model that can be adapted to local conditions across Indonesia and other developing countries.

2. Literature Review

Various solar-powered water treatment systems have been developed as sustainable clean water solutions. This section reviews several system configurations that are relevant to the present study.

An AGMD (Air Gap Membrane Distillation) water treatment system integrated with solar cells consists of three main sub-systems: (1) a solar photovoltaic (PV) system with a 6.6 kW panel array, a 5 kVA inverter, and batteries supplying electricity for 6 hours per day; (2) a solar thermal system utilizing evacuated tube collectors that produce hot water at 60 °C; and (3) a purification sub-system consisting of two AGMD modules, pumps, a heat exchanger, and a cooling tower.

The system operates by pumping groundwater contaminated with fluoride into the solar collector for heating, after which the water flows into the AGMD module, creating a vapor pressure difference across a hydrophobic membrane. Water vapor passes through an air gap and condenses, producing high-quality purified water with fluoride content below 1.5 mg/L and a production

capacity of 111.6 liters per day. The modular design allows easy scalability and safe operation at atmospheric pressure [20].

Another study designed a vertically integrated water treatment system within a building using evacuated solar tubes with a diameter of 58 mm and a length of 1.8 m, equipped with nine polypropylene hollow-fiber membranes (2.7 mm diameter, 0.4 m length, total membrane area 0.03 m²). The main construction components included an aluminum Compound Parabolic Collector (CPC) measuring 0.18 m × 1.8 m with reflective mirror walls for solar concentration, a vacuum pump operating at 15 kPa, and a 5-liter condensation tank.

A helical baffle design (50 mm pitch, 30° angle) was incorporated to increase turbulence and improve flux by 6.3%. The optimal ratio between membrane area and solar collector area was found to be 1:10. This system was capable of heating water from 20 °C to 60 °C within 15 minutes with a thermal efficiency of 64%, producing approximately 40 liters of clean water per day [21].

The BIPSET system was designed to integrate a solar still, PV panels, and a solar chimney into a building prototype at a 0.6 scale. The solar still employed a stainless-steel tray with reused jute cloth coated with charcoal powder as the evaporator, 4 mm thick glass as the condenser, and aluminum sheets as the external condenser. Two 80 W monocrystalline PV panels were installed at a 10° inclination, forming an air channel (D1) with a 5 cm-deep aluminum sheet.

An aluminum chimney measuring 1.4 m × 1.2 m × 0.1 m connected the components through two air channels (D1 and D2). The structure was built using a lightweight steel frame and plywood with 5 cm polyurethane foam insulation to minimize heat loss, resulting in an efficient, integrated passive system [22].

Based on the literature review above, it can be concluded that the integration of solar technology with water purification systems demonstrates significant potential in terms of energy efficiency, produced water quality, and ease of implementation. These findings reinforce the feasibility of developing integrated, solar-powered clean water treatment systems that are suitable for building-integrated applications in remote areas.

3. Method

This study employs the Research and Development (R&D) method, which was selected because it aligns with the research objective of designing and constructing an integrated solar-powered clean water treatment system for smart buildings in remote areas [23]. This approach comprises systematic stages beginning with problem identification, system design, prototype fabrication, and performance evaluation, ultimately producing a measurable and practically implementable sustainable technological solution.

3.1. Problem Analysis

This stage involves identifying the problem of limited access to clean water in remote areas due to the absence of electrical infrastructure and the high operational costs of conventional systems. In addition, the average potential of solar energy is analyzed as a feasible autonomous energy source that can be integrated with water treatment systems. The analysis also includes an assessment of water source pollution levels and local community daily water consumption requirements, which serve as the basis for determining the system's capacity.

3.2. Design

The system design integrates photovoltaic (PV) solar panels, an inverter, batteries, a pre-treatment unit, multi-stage filtration, ultraviolet disinfection, and real-time monitoring sensors. This stage also includes simulation and calculation of energy loads and water production capacity to ensure alignment between the solar energy supply and the operational demands of the system.

3.3. Prototype Fabrication

Prototype fabrication includes the installation of the water treatment system, loading of carbon filter materials, filter membranes, pumps, ultraviolet (UV) sterilization units, storage tanks, and polycrystalline solar panels. All components are integrated into the framework of a smart building at a scale appropriate to meet village community needs. The fabrication process is carried out in stages, with functional testing conducted on each component before full system integration to ensure optimal performance.

3.4. Implementation

The system is operated under field conditions with a target clean water production capacity of 1,000–1,500 liters per day. This stage ensures that the output water quality meets established water quality testing standards and that the system operates independently using solar energy as its sole electricity source. Implementation is conducted in a representative remote area to evaluate the system's adaptability to local environmental and social conditions.

3.5. Evaluation

System performance is evaluated comprehensively, covering thermal efficiency, output water quality, energy consumption, and operational reliability. The evaluation results are compared with design parameters to determine the level of success and to formulate recommendations for further development. Evaluation data are collected through real-time monitoring sensors and analyzed statistically to generate valid and objective conclusions.

4. Results

4.1. Design of the Water Filtration System and Implementation in a Smart Building

Figure 1 illustrates the design of the house where the water filtration system is installed. This design was created using the SketchUp application to provide a clear and detailed representation of the system layout to be implemented. Complete design details can be seen in Figure 1, which shows the building structure along with the comprehensive placement of the water filtration system components.



Figure 1. Water Filter Design and Implementation in a Smart Building.

Figure 1 presents the design of the water filtration system components and their implementation within a smart building. The design consists of two main sections: the component design of the

filtration system and the residential building design that serves as the implementation site for the system.

Furthermore, Figure 2 illustrates the design of the house used as the implementation site for the solar-powered clean water treatment system. The building layout was planned to accommodate the integration of water treatment units, solar energy components, electrical panels, and water storage infrastructure within a smart-building concept. This design demonstrates how building-scale clean water infrastructure can be incorporated into residential structures in remote areas without extensive structural modification, ensuring functional efficiency and ease of system operation and maintenance.

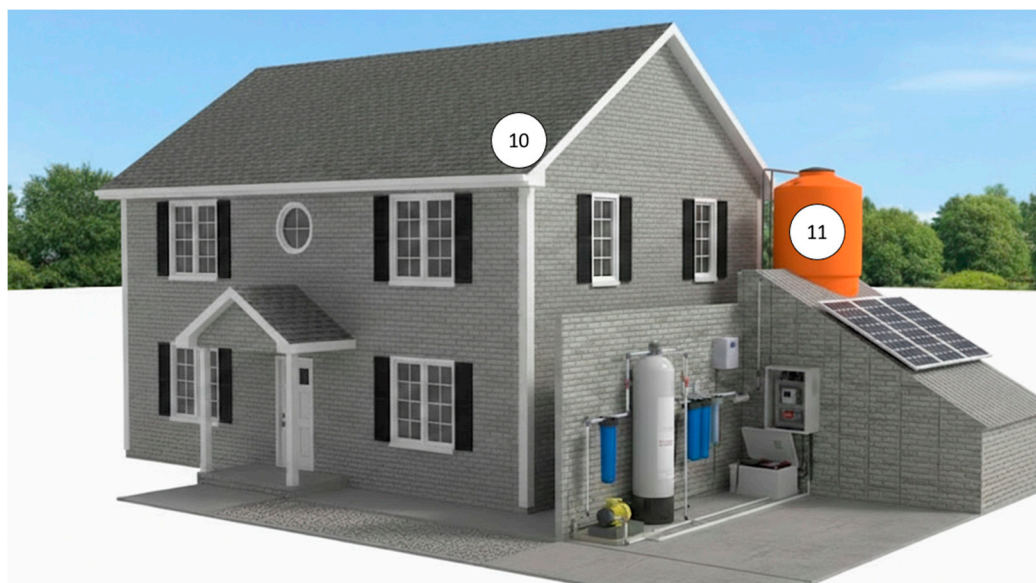


Figure 2. House Building Design.

Detailed component specifications in Figures 1 and 2 are listed in Table 1. The table summarizes the main components and technical specifications of the integrated solar-powered clean water treatment system implemented in the smart building. The table includes pumping units, multi-stage filtration components, ultraviolet sterilization, solar power supply, electrical protection devices, monitoring systems, and water storage facilities. The listed specifications highlight design considerations for off-grid operation, energy efficiency, and compliance with clean water quality standards, supporting the system's reliability and sustainability for building-scale applications in remote areas.

Table 1. Details of Water Filter Components and Implementation on a Smart Building.

No	Component Name	Specification
1	Water Pump	DC centrifugal pump, 12–24 V, capacity 1,000–1,500 L/day
2	Floss or Mud Filter	Fibrous filter media, 5–10 μm pore size
3	Carbon Filter	Activated carbon media, 0.5–1 mm granule size
4	Filter Scoop and Water hyacinth cellulose	Natural cellulose-based bio-filter material
5	IoT Monitoring Box	Microcontroller with Wi-Fi, pH (0–14), temperature (0–100 $^{\circ}\text{C}$), TDS (0–2,000 ppm)
6	UV Water Sterilizer	UV-C lamp, 254 nm wavelength
7	Battery-Powered Solar Panel	Deep-cycle battery, 50–100 Ah capacity
8	Electrical Panel Box	MCB, voltage regulator, safety switch enclosure

9	Solar Panel	Polycrystalline PV module, 300–500 Wp, 18–20% efficiency
10	House or Building	Smart-building installation structure
11	Water Tank	Food-grade polyethylene, ±1,500 L capacity

Table 1 presents a detailed list of all components used in the smart-building water filtration system. The system consists of eleven main components that are interconnected, starting from the water pump that drives water flow, floss filters, carbon filters, and UV sterilizers to ensure clean and safe water quality. In addition, the system is equipped with solar panels as a renewable energy source and an IoT monitoring unit that enables real-time and efficient system condition monitoring.

4.2. The Use of Eco-Friendly Water Hyacinth Cellulose Filters

In this water treatment system, an eco-friendly filter material based on water hyacinth cellulose, known as the Water Hyacinth Cellulose Membrane Filter, is used. This filter material was chosen because water hyacinth (*Eichhornia crassipes*) has a high cellulose content, reaching 72.63%, making it effective as an absorbent material. Additionally, water hyacinth contains active compounds such as saponins, flavonoids, polyphenols, and alkaloids that function as natural antibacterial agents. Using water hyacinth as a filter raw material also provides a dual benefit: it simultaneously controls the excessive growth of water hyacinth weeds in Lake Cinta's waters, which is a consequence of eutrophication.

Figure 3 shows the process of producing water hyacinth cellulose filters used as an eco-friendly filtration material in the clean water treatment system. The process begins with harvesting water hyacinth, followed by cleaning, mechanical processing, and cellulose extraction to form membrane-based filter materials. The resulting cellulose membrane exhibits a porous structure with high adsorption capacity, enabling effective removal of suspended particles, dissolved contaminants, and microbial pollutants while utilizing locally available biomass resources.

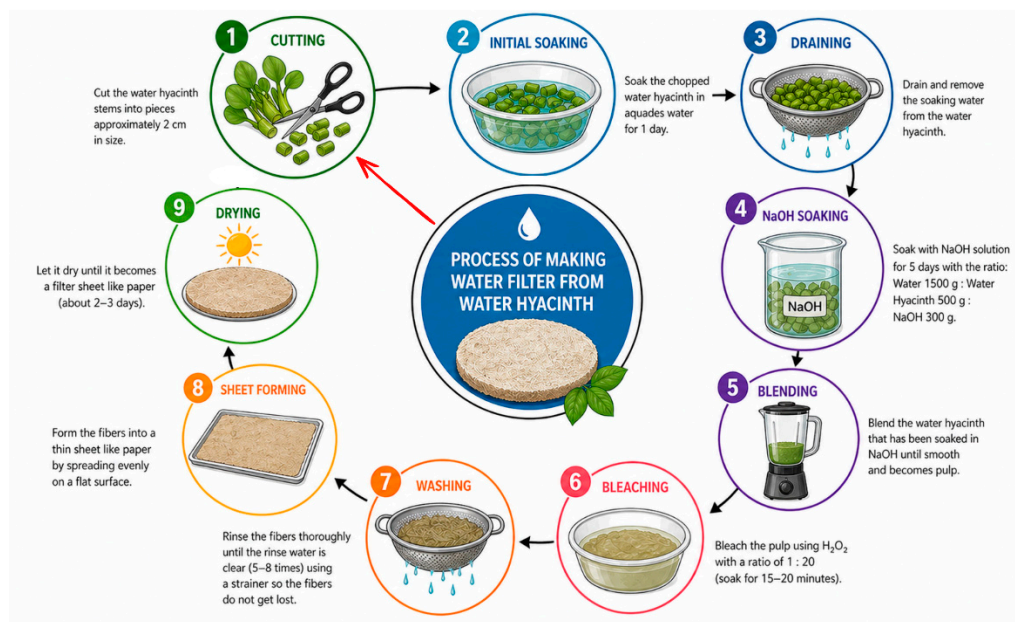


Figure 3. The process of making water hyacinth cellulose filters.

Water hyacinth harvested from Lake Cinta is then processed through a series of steps to produce cellulose membrane sheets. Cellulose acts as a porous polymer capable of forming a layer with a uniform chain surface, making it effective in absorbing surrounding contaminants, including heavy

metals, pathogenic bacteria, and suspended particles. It is this porous nature that makes water hyacinth cellulose membranes superior as a water filtration medium, particularly in potable water treatment plants.

Figure 4 presents the structural design of the water hyacinth cellulose membrane filter and its placement within the multi-stage clean water treatment system. The filter is designed to allow uniform water flow across the membrane surface, maximizing contact between the treated water and cellulose fibers. This design enhances contaminant removal efficiency while maintaining system stability and compatibility with subsequent filtration and ultraviolet disinfection stages.

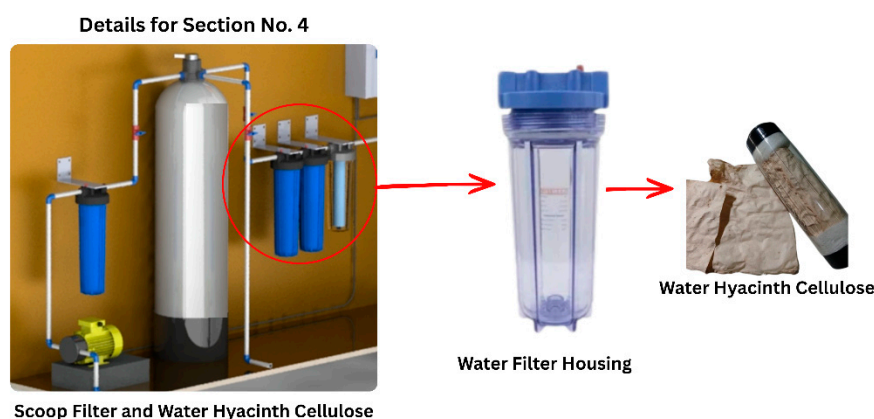
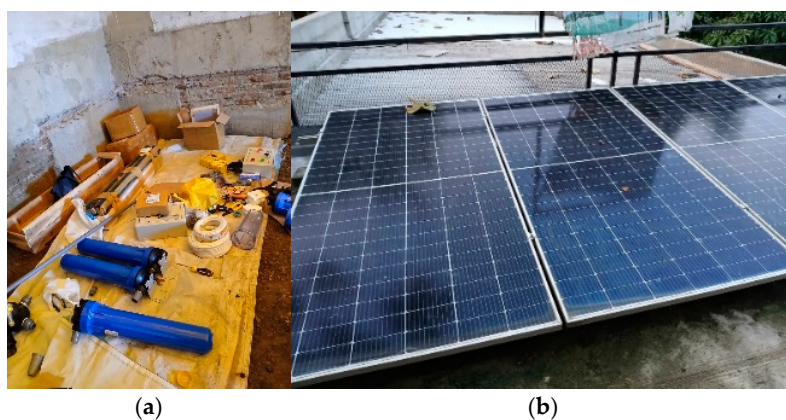


Figure 4. Design of the Water Hyacinth Cellulose Membrane Filter in a Clean Water Treatment System.

4.2. Installation of Components and Filtration System

This stage involves the installation of the water filtration system, which is a critical process to ensure that all components function properly and optimally. The installation process includes assembling components carried out carefully and systematically by experienced technicians. Each component is installed in accordance with the predetermined design, starting from the water pump, filtration units, UV sterilizer, to the solar panels.

Details of the installation process are shown in Figure 5, which depicts technicians assembling all system components thoroughly and precisely to ensure full system integration. Subsequently, the electrical installation process was performed in compliance with applicable safety standards. The electrical system was designed to support optimal and efficient operation of all components.





(c)

Figure 5. (a) Preparation of filter parts and components, (b) results of installing the solder cell, (c) technician installing the system equipment.

Figure 5 illustrates key stages of system assembly and installation. Figure 5(a) shows the preparation of filter parts and supporting components prior to system integration. Figure 5(b) depicts the installation of soldered solar cell connections to ensure reliable electrical power delivery. Figure 5(c) presents technicians installing and positioning the water treatment equipment at the deployment site. These stages reflect a systematic installation process aimed at ensuring mechanical stability, electrical safety, and optimal system performance.

The system is also equipped with an emergency stop as an additional safety feature, which allows the entire system to be shut down automatically or manually in the event of sudden incidents that could endanger users or equipment. Furthermore, the system includes a Miniature Circuit Breaker (MCB), which functions as an automatic electrical protection device that disconnects current during overloads or short circuits [24]. These safety features are essential to ensuring overall system safety. Details of the safety system are shown in Figure 6, which presents the emergency stop installed on the filtration system.

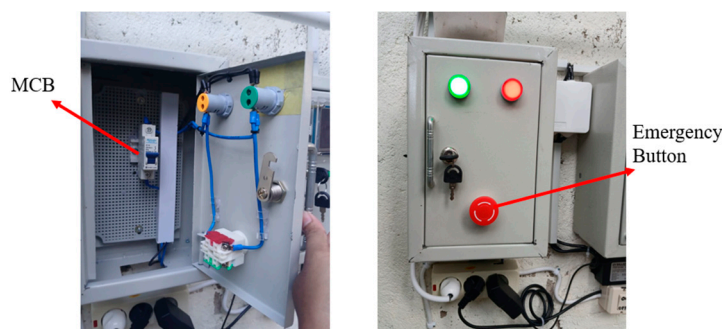


Figure 6. Emergency Stop System as a safety measure for water filter systems to ensure user safety in the event of a sudden incident.

4.3. Integration with a Smart Monitoring System

The system is integrated with IoT technology for monitoring water quality. As shown in Figure 7, the system uses Wi-Fi-based IoT connected to sensor devices. Water quality monitoring results, including pH, temperature, and total dissolved solids (TDS), can be observed in real time through a monitoring application. Figure 7 also shows the Blynk application interface used as the real-time water quality monitoring platform. Through this interface, users can directly monitor pH, temperature, and TDS values via a smartphone. Data are transmitted from Wi-Fi-based sensor devices to the Blynk application using an internet connection, enabling users to monitor water conditions anytime and anywhere.



Figure 7. Integration with Intelligent Monitoring System.

4.4. Water Quality Results After Filtration

Water quality testing was conducted to evaluate the performance of the proposed solar-powered clean water treatment system by comparing parameters before and after the filtration process. Table 2 presents a comparison of key microbiological, physical, and chemical water quality parameters, including temperature, pH, total dissolved solids (TDS), and *Escherichia coli*. This assessment was carried out to demonstrate the effectiveness of the designed filtration system in improving raw water quality. All parameters were measured using calibrated sensors that had been laboratory-tested to ensure measurement accuracy and reliability. The obtained results were then evaluated against the Indonesian clean water quality standards as stipulated in Ministry of Health Regulation No. 2 of 2023 to determine system compliance.

Table 2. Comparison of Water Quality Parameters Before and After Filtration Based on Indonesian Clean Water Standards (Ministry of Health Regulation No. 2 of 2023).

Parameter	Unit	Maximum Standard	Before Filtration	After Filtration	Reduction	Status
1. Microbiological						
<i>E. coli</i>	CFU/100 mL	0	100	0	100%	Reduced by 100%
Total Coliform	CFU/100 mL	0	7	0	100%	Reduced by 100%
2. Physical						
Total Dissolved Solids (TDS)	mg/L	< 300	450	218	51.6%	Reduced by 51.6%
Turbidity	NTU	< 3	1.0	0.4	60%	Complies
Temperature	°C	Ambient ± 3	21	21	-	Complies
3. Chemical						
Dissolved Manganese	mg/L	0.1	30	0.01	99.97%	Reduced by 99.97%
Nitrate	mg/L	20	6	3	50%	Complies
pH	-	6.5–8.5	8	8	-	Complies

Based on Table 2, the filtration results show a significant improvement across all water quality parameters. Water temperature remained stable at 21 °C before and after filtration, indicating no thermal interference from the filtration process. pH remained unchanged at 8, still within the acceptable range of 6.5–8.5 as stipulated by Minister of Health Regulation No. 2 of 2023. TDS was

reduced significantly from 450 mg/L to 218 mg/L, representing a 51.6% reduction and bringing the value well below the maximum threshold of 300 mg/L. Furthermore, E. coli bacteria were completely eliminated, decreasing from 100 CFU/100 ml to 0 CFU/100 ml, and Total Coliform was equally reduced from 7 CFU/100 ml to 0 CFU/100 ml, both meeting the required standard of 0 CFU/100 ml. Dissolved manganese also showed a dramatic reduction from 30 mg/L to 0.01 mg/L, a decrease of 99.97%, far below the maximum allowable limit of 0.1 mg/L.

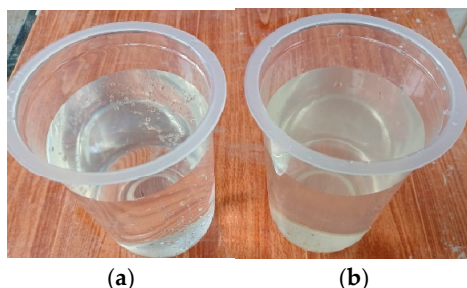


Figure 8. Comparison of water (a) water after filtering, (b) water before filtering.

Figure 8 presents a visual comparison of water quality before and after filtration using the designed system. In Figure 8(a), the water appears clear and clean after passing through the filtration process, whereas Figure 8(b) shows the water's turbid and contaminated condition before filtration. This visual difference demonstrates that the filtration system operates effectively in improving water clarity.

4.5. Evaluation of System Implementation

Based on the evaluation results of the integrated solar-powered clean water treatment system, several aspects require improvement to optimize overall system performance. The storage tank capacity, initially limited to 1,500 liters, is recommended to be increased to 2,500-3,000 liters to meet the needs of a larger population and to account for variations in solar radiation intensity during the rainy season.

In addition, system development should not be limited solely to clean water treatment for direct consumption but should also be expanded to support the production of bottled water that meets national health standards. In future developments, the system may also be enhanced with automated IoT-based water quality monitoring modules, increased solar panel capacity, and the addition of wastewater treatment units for filtration byproducts to ensure comprehensive environmental sustainability.

4. Conclusions

This study successfully designed and constructed an integrated solar-powered clean water treatment system that is effective for deployment in smart buildings in remote areas. The developed system consists of eleven main components that are fully integrated, including a water pump, floss filter, carbon filter, ultraviolet sterilizer, polycrystalline solar panels, and an IoT-based monitoring system using the Blynk platform.

Water quality testing results indicate a significant improvement across all evaluated parameters, including the complete elimination of E. coli bacteria from 100 CFU/100 ml to 0 CFU/100 ml and Total Coliform from 7 CFU/100 ml to 0 CFU/100 ml, a reduction in Total Dissolved Solids (TDS) from 450 mg/L to 218 mg/L (51.6%), a dramatic decrease in dissolved manganese from 30 mg/L to 0.01 mg/L (99.97%), and a reduction in nitrate from 6 mg/L to 3 mg/L, while pH remained stable at 8 and water temperature was unchanged at 21 °C throughout the filtration process. All output parameters met clean water quality standards for hygiene and sanitation purposes as stipulated in Minister of Health Regulation No. 2 of 2023, demonstrating that the Water Hyacinth Cellulose Membrane Filter system

utilizing water hyacinth cellulose membrane is capable of effectively and optimally processing contaminated lake water into high-quality clean water.

The integrated solar-powered water treatment system is proven to operate independently without reliance on the national electricity grid, achieving a clean water production capacity of 1,000–1,500 liters per day. This performance confirms the system's feasibility and sustainability as a solution for communities in remote areas. Furthermore, the integration of IoT technology enables real-time monitoring of water quality parameters via smartphones, enhancing operational efficiency and ease of system management.

For future development, it is recommended that the storage tank capacity be increased to 2,500–3,000 liters to anticipate variations in solar radiation intensity during the rainy season and to support expanded system utilization. The system's functionality may also be extended beyond household water treatment toward the production of bottled drinking water that complies with national health standards. Overall, this research provides a model for sustainable technology implementation that can be adapted across various regions in Indonesia as well as other developing countries, contributing to the achievement of the Sustainable Development Goals.

Author Contributions: Khakam Ma'ruf: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. Rizal Justian Setiawan: Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. Yudi Prasetyo: Funding acquisition, Investigation, Visualization, Writing – original draft. Ginanjar Dwi Prasetyo: Formal analysis, Resources, Writing – review & editing. Rifki Alfirahman: Funding acquisition, Project administration, Resources. Paskalis Guntur Hikmat: Data curation, Funding acquisition, Software, Validation. Naufal Yasir: Funding acquisition, Project administration, Writing – review & editing. Redi Andriansah: Data curation, Funding acquisition, Writing – original draft. Devi Nurcahyaningtyas: Funding acquisition, Software, Writing – original draft. Mantahari Hasibuan: Funding acquisition, Formal analysis, Resources. All authors have read and agreed to the published version of the manuscript.

Funding: We would like to thank Indonesia Endowment Fund for Education (LPDP) from the Ministry of Finance Republic Indonesia for granting the financial support in this research. This assistance is very important in our research because this support allows us to conduct research that is beneficial to the environment, education, and society.

Institutional Review Board Statement: Not applicable. This study did not involve human participants, human data, or animals.

Informed Consent Statement: Not applicable. This study did not involve human subjects.

Data Availability Statement: The data presented in this study are included within the article.

Acknowledgments: We would like to thank the Indonesia Endowment Fund for Education (LPDP) from the Ministry of Finance of the Republic Indonesia for granting this research.

Conflicts of Interest: The authors declare no conflicts of interest.

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