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Design and Development of a Smart Portable Water Purification System

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ABSTRACT

Access to clean drinking water remains a critical challenge for individuals in remote, off-grid, or temporary living situations such as travelers, campers, and emergency responders. This project presents the design and development of a Smart Portable Water Purification System that addresses this need through a compact, solar-powered, and IoT-integrated solution. The system utilizes a multi-stage filtration process including sediment, pre-carbon, reverse osmosis, post-carbon, and silver carbon filters to effectively remove physical impurities, chemical contaminants, and biological hazards. Real-time water quality monitoring is achieved using TDS and pH sensors, while a Raspberry Pi Pico W microcontroller enables wireless control and monitoring via a custom-built graphical user interface accessible through a local Wi-Fi access point. Performance evaluations showed a significant improvement in water quality, with pH values normalized to safe ranges. Despite low to moderate filtration speeds and unoptimized data handling, the results validate the system's effectiveness and usability in field conditions. Recommendations for future enhancements include improving power efficiency, filtration speed, communication protocols, sensor integration, and mechanical design for better portability and environmental durability. The final prototype demonstrates a reliable, user-friendly, and sustainable approach to decentralized water purification.

Keywords: IoT, Sustainable Energy, Water Purification

1. INTRODUCTION

Access to clean drinking water remains a persistent issue for travelers, campers, and individuals in temporary accommodations, as traditional and many modern portable purification methods fail to adequately address capacity, contaminant range, and maintenance challenges [1], [2], [3]. Thus, a Smart Portable Water Purification System can be designed and developed, able to offer a comprehensive solution by integrating advanced, multi-stage filtration including sediment removal, activated carbon, UV sterilization, and reverse osmosis into a lightweight, solar-powered design. Equipped with IoT sensors for real-time water quality monitoring and supported by a mobile app for user guidance and maintenance alerts, the system is engineered to ensure safe, accessible drinking water even in remote locations. Its objectives are to guarantee high water quality, promote sustainability and portability, and reduce waterborne health risks, ultimately improving public health outcomes in mobile or off-grid environments.

A collection of recent studies highlights the growing effectiveness and relevance of advanced point-of-use (POU) water treatment systems in addressing water quality challenges across diverse environments. Research demonstrated that reverse osmosis (RO) and dual-stage filters are highly effective at removing harmful PFAS contaminants from residential water, achieving over 97% removal rates and significantly outperforming simpler pitcher-style filters, though emphasizing the need for regular maintenance [4]. Another study further supported the value of POU systems—particularly activated carbon and RO filters—in removing a wide range of pollutants like chlorine, organic compounds, and dissolved salts. These pollutants correspond to

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key water quality parameters such as pH, TDS, and Free Cl, as outlined in Table 1. They also noted a gap in standardization and the limitations of existing "smart" filter systems, underscoring the importance of user-focused design [5]. Another study evaluated RO-based systems in rural China and found that while they improved compliance with water quality standards, their effectiveness diminished over time without proper filter maintenance highlighting, the critical role of service life in long-term performance [6]. Adding a modern layer a researcher proposed integrating AI-powered optical systems to enhance real-time monitoring of water quality parameters such as pH, dissolved oxygen, and ammonia nitrogen. Their findings revealed notable gains in detection accuracy, responsiveness, and efficiency. Together, these studies underscore the strong potential of combining multi-stage filtration, smart monitoring, and AI-enhanced sensing to build more reliable, adaptive, and user-friendly water purification solutions for both developed and resource-limited settings [7].

Recent studies have demonstrated the effectiveness of integrating renewable energy and IoT technologies into modern water purification systems. One study focused on the implementation of solar-powered filtration, highlighting how photovoltaic (PV) panels can provide reliable energy for water treatment in off-grid locations, provided the system is properly sized and economically viable [8]. Building on this concept, more advanced systems now incorporate multi-stage filtration processes including activated carbon, reverse osmosis, and UV sterilization alongside smart monitoring tools for enhanced safety and usability. Another study emphasized the role of IoT-based monitoring, using smart sensors to track critical water quality parameters such as pH, TDS, turbidity, and temperature. These systems compare sensor readings to international benchmarks like WHO and EPA standards, automatically alerting users when unsafe conditions are detected. Together, these developments form the basis for intelligent, sustainable, and user-friendly purification systems ideal for remote and mobile applications.

In terms of connectivity, the research outlines various communication protocols suitable for water monitoring systems, including Wi-Fi for high bandwidth environments, GSM and 4G for mobile deployments, and LoRa for long range, low power applications ideal in remote or off grid locations. The study also emphasizes the role of GUIs, such as mobile apps and cloud dashboards, which allow users to visualize water quality metrics in real time, receive alerts, and monitor system health. The integration of cloud platforms and microcontrollers enables seamless data collection, storage, and analysis. Overall, the study not only reviews current techniques but also provides design recommendations for building robust, real time, and user-friendly smart water monitoring solutions based on established health standards [9].

Table 1 Parameters of safe limits for drinking water

Parameter	**Comments**	**Safe Limits**	**Unit**
EC	It is the ability of an aqueous solution to allow electric current. It is generally used to measure salinity in water.	300~800	μS/cm
pH	pH=−log[H+]pH=−log[H+]; effective hydrogen ion concentration.	6.5~8.5	pH
Turb	Solids suspended in water, which hurdle with light transmission.	1.0~5.0	NTU
TDS	It is the amount of organic and inorganic materials.	600~1000	mg/L
DO	Amount of oxygen dissolved in water.	5.0~6.0	mg/L
Free Cl	It is responsible to chlorinate microbes in water.	0.2~5.0	mg/L
T	It has high correlation with DO and pH.	10°~22°	C

2. MATERIAL AND METHODS

This chapter outlines the materials, components, and methodologies used in the development of the Smart Portable Water Purification System. It presents a comprehensive overview of the design and implementation strategies adopted to ensure effective water filtration, robust mechanical construction, reliable power supply, intelligent control logic, and seamless IoT integration.

2.1 Water Purification

The filtration process in this project is designed to ensure comprehensive purification of water by integrating multiple filtration stages within a compact, portable system. As water enters the unit, it passes sequentially through a series of filtration elements aimed at removing physical impurities, chemical contaminants, and biological hazards. This multi-layered approach enhances the overall effectiveness of the system and ensures the production of safe drinking water in a variety of environments. The general flow of water through the filtration stages is illustrated in Figure 1, which provides a simplified representation of the treatment pathway from input to output. Further details on the individual filtration components and their roles will be presented in the relevant subsections.

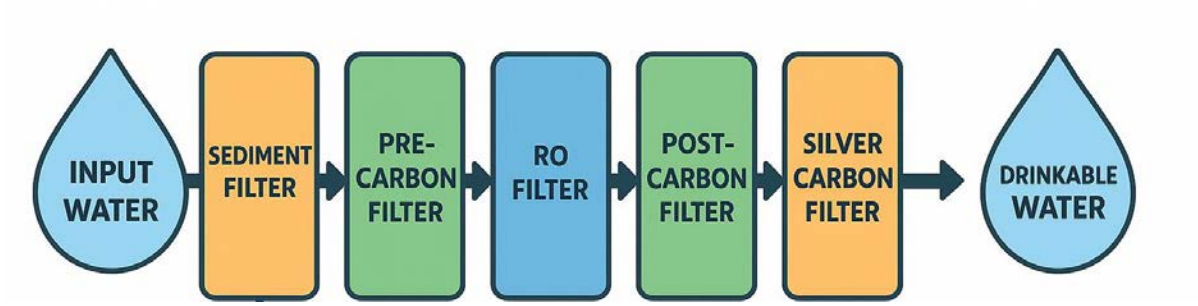

Figure 1. Water flow in the filter system

The Smart Portable Water Purification System employs a five-stage filtration process designed to ensure comprehensive removal of contaminants from untreated water sources. The first stage, a sediment filter, removes large physical particles such as sand, rust, and debris, protecting the downstream components from clogging and damage. The second stage, a pre-carbon (activated carbon) filter, targets chemical pollutants like chlorine, VOCs, and pesticides, improving taste and shielding the reverse osmosis membrane from chemical degradation [10].

The third and most critical stage, the reverse osmosis (RO) filter, uses a semi-permeable membrane to eliminate dissolved salts, heavy metals, nitrates, and biological contaminants such as bacteria and viruses. This stage ensures a high level of purification through pressure-driven molecular separation [11]. The fourth stage, the post-carbon filter, functions as a polishing layer, removing any remaining chemical residues and enhancing the water's taste and smell through further adsorption [12].

The final stage, the silver-impregnated carbon filter, integrates antimicrobial protection by combining activated carbon with silver nanoparticles. This filter not only continues chemical adsorption but also inhibits microbial growth within the filter media, preventing recontamination. Together, these five filtration stages deliver safe, clean, and palatable drinking water by addressing physical, chemical, and biological impurities effectively [12]. Table 2 summarizes the functions and contaminants removed at each stage of the filtration process.

Table 2 Filters functions

Stage	Filter Type	Primary Function	Contaminants Removed
1	Sediment Filter	Initial filtration stage that protects downstream filters	Physical impurities (sand, rust, silt, debris)
2	Pre Carbon Filter	Adsorption of chemicals to protect RO membrane and improve taste/odor	Chlorine, VOCs, pesticides, organic chemicals
3	Reverse Osmosis (RO)	Core filtration that removes dissolved and microscopic contaminants	Heavy metals, salts, nitrates, fluoride, bacteria, viruses
4	Post Carbon Filter	Final taste and odor polishing	Residual chlorine, VOCs, Unpleasant taste and odor
5	Silver Impregnated Carbon	Antibacterial protection and enhanced chemical removal	Microbial growth (E. coli, Salmonella), remaining organic/inorganic traces

2.2 Mechanical Design

The mechanical design of the Smart Portable Water Purification System shown in Figure 2 is developed to balance durability, portability, and functionality within a compact form factor. The overall dimensions of the device are 41 × 33 × 31 cm, allowing it to remain portable while accommodating all critical components including the filtration stages, water tank, pump, power system, and control unit.

The outer enclosure of the system is fabricated from Polylactic Acid (PLA), a biodegradable thermoplastic known for being lightweight and structurally stable ideal for 3D printing and prototyping. PLA provides sufficient strength for field use while keeping the total dry weight of the system, ensuring ease of transport for outdoor or remote applications.

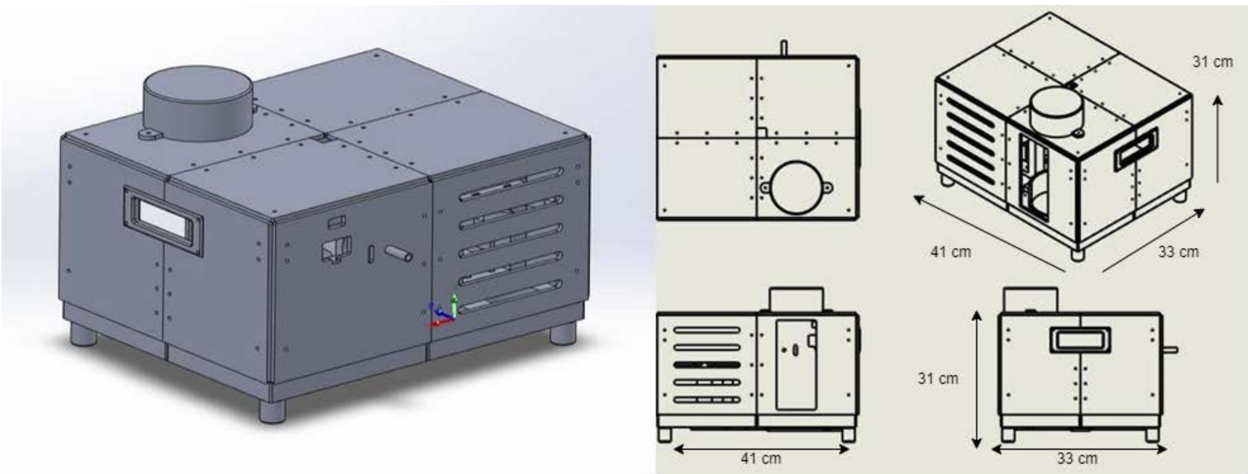

Figure 2. Mechanical design

Internally, the system houses a 1.8-liter water tank made from food grade plastic, offering a safe and sealed environment for storing filtered water. The tank is integrated seamlessly into the lower section of the device, optimizing space usage and center of gravity. Additionally, a secondary internal enclosure made of PVC is installed to secure the electronic control components, such as the microcontroller, relays, and sensors. PVC is selected for its non-conductive properties, resistance to moisture, and structural rigidity, which protects the sensitive electronics from water ingress or physical damage. Together, these material choices and dimensions reflect a design optimized for durability, user convenience, and safe operation in various environments, from outdoor camping to emergency relief scenarios.

2.3 Power Management System

The power system of the Smart Portable Water Purification System is built to ensure reliable, off-grid functionality while maintaining a compact and portable design. It uses a 12V, 5W solar panel as its primary renewable energy source, which captures sunlight and converts it into electrical energy to charge a 12V lithium polymer (LiPo) battery. This battery stores energy and supplies consistent power to essential components such as the water pump, sensors, and control electronics, even in low-light conditions. The system is designed for compatibility with low-power hardware and optimized for energy efficiency, making it well-suited for outdoor and emergency use. By combining solar charging with lightweight energy storage, the design eliminates dependency on external power sources and supports use in remote or temporary settings.

2.4 Control System

The control system is the core intelligence of the Smart Portable Water Purification System, responsible for automating operations, managing sensor data, and executing user commands. This section provides an overview of the microcontroller platform selected for the system and details the integration of key sensors and actuators. The controller serves as the central hub, interfacing with input devices such as water quality sensors, and controlling outputs like pumps, valves, and indicator modules. Through real time monitoring and decision making, the control system ensures the filtration process operates efficiently, safely, and in response to changing water conditions. The following subsections will outline the hardware used, the logic behind component interaction, and the role of each element in enabling intelligent system behavior. Figure 3 illustrates the system diagram.

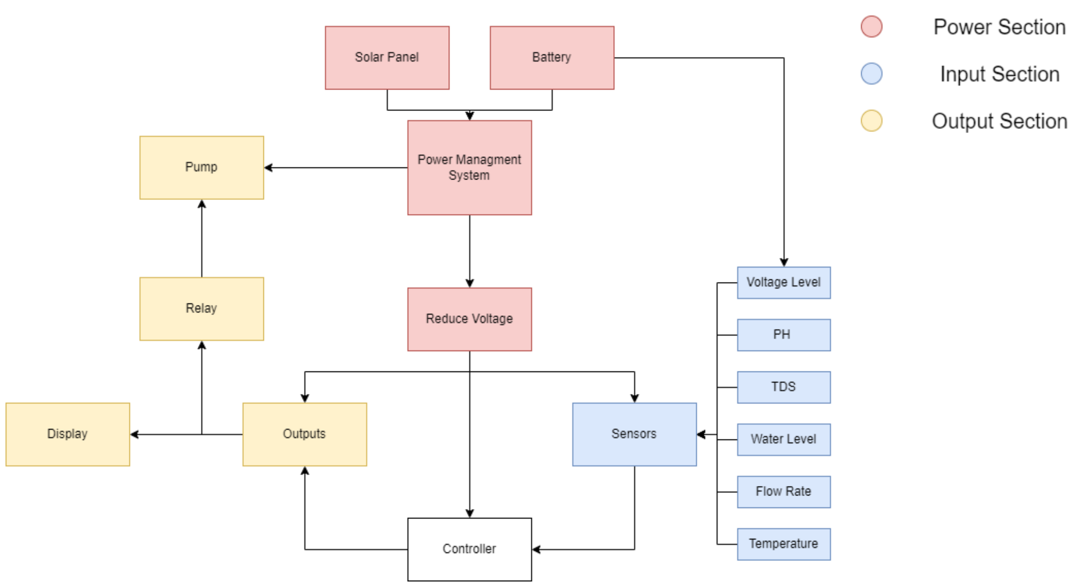

Figure 3. System diagram

The control system of the Smart Portable Water Purification System is centered around the Raspberry Pi Pico W, a compact microcontroller known for its energy efficiency, wireless capability, and adaptability. It manages the overall operation by interfacing with all sensors and actuators, handling tasks such as data collection from pH and TDS sensors, activating pumps, and communicating system status wirelessly. With its dual-core ARM Cortex M0+ processor and built-in Wi-Fi, the Pico W enables real-time control and supports remote monitoring making it an ideal choice for compact, off-grid, IoT-based water treatment systems [13].

The system uses various input devices and sensors to monitor environmental and water quality conditions, including temperature, flow, pH, TDS, voltage, and water level. A power switch and manual button ensure safe control. An OLED display shows real-time data, while a relay-controlled filtration pump operates automatically. A manual dispensing pump allows users to control water output. These components enable efficient water purification, reliable performance, and clear user interaction.

2.5 IoT Integration

The Smart Portable Water Purification System leverages IoT technology to provide real-time monitoring, control, and interaction without reliance on external internet access. By utilizing the built-in Wi-Fi capability of the Raspberry Pi Pico W, the system acts as a self-hosted access point, allowing any nearby Wi-Fi-enabled device to connect directly. This configuration supports mobile and off-grid deployment, enabling users to track filtration performance, water quality, and system status efficiently. The use of lightweight communication protocols ensures responsive and energy-efficient operation suitable for low-power environments.

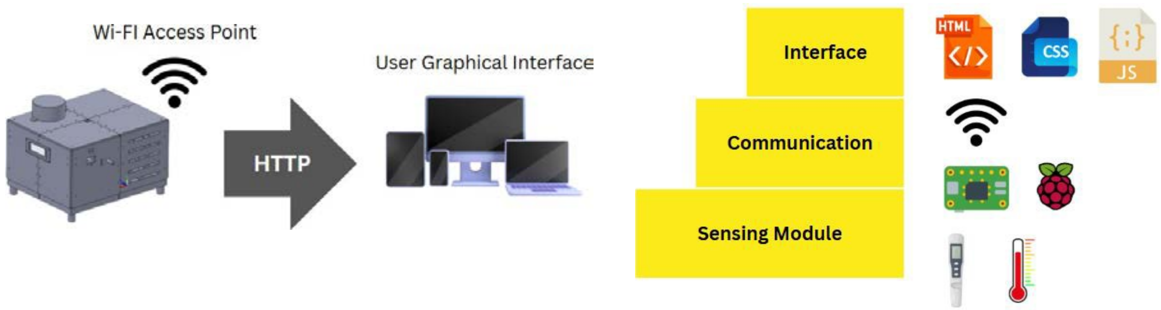

Figure 4. IoT communication architecture system

As illustrated in Figures 4, the system architecture includes three primary layers: the sensing module, the communication layer, and the interface layer. The sensing module is responsible for real-time water quality assessment, focusing on pH and Total Dissolved Solids (TDS) both critical indicators of potability. These sensors feed data directly to the Raspberry Pi Pico W, which processes and displays the information through the user interface. If any readings fall outside of safe thresholds, the system alerts the user, enabling timely response or maintenance.

The communication system plays a central role in enabling wireless data exchange between the controller and external devices. Configured as a Wi-Fi Access Point (AP), the device creates a local wireless network that facilitates communication using HTTP protocols. This setup allows structured data exchange such as sensor readings and operational status without the need for cloud connectivity or external routers. It ensures stable, secure, and localized control, forming the backbone of the IoT integration. The user interface is developed as a lightweight web application using HTML, CSS, and JavaScript, providing a clear and responsive layout accessible through any modern browser. Hosted directly on the Raspberry Pi Pico W's embedded HTTP server, the interface enables users to monitor system metrics and control functions intuitively. This self-contained, real-time dashboard enhances the overall user experience by offering seamless access to system data and controls, even in remote and infrastructure-limited environments.

3. RESULTS AND DISCUSSION

As shown in Figure 5, the final assembled prototype of the Smart Portable Water Purification System demonstrates a well-integrated design that accommodates all major components filtration units, storage tank, power system, and control electronics within a compact and durable enclosure. The arrangement reflects the system's emphasis on portability, functionality, and ease of use, especially in off-grid and field environments.

Figure 5. Final prototype

Table 3 presents the physical specifications of the prototype, confirming its suitability for mobile applications. With overall dimensions of 41 × 33 × 31 cm and a weight of 5.0 kg when empty and 8.4 kg when full, the device remains lightweight and compact, enabling users to easily carry and deploy it in remote or temporary locations. The enclosure includes a built-in side handle cut-out, enabling easy manual transport and supporting the device's intended field portability. These characteristics validate the success of the mechanical design in meeting both functional and transport requirements.

Table 3 Physical specifications of the final prototype

Parameter	Value	Unit	Description
System Dimensions	41 × 33 × 31	cm	Overall size of the device
Weight (No water in the system)	5.0	kg	Total weight when there is no water in the system
Weight (System full of water)	8.4	kg	Total weight when the tank and pipes are full of water

Table 4 illustrates the system's effectiveness in stabilizing pH levels under varying conditions. Water samples altered by lemon, tea, salt, and baking soda were all brought within or close to the safe drinking range of 6.5 to 7.5 pH after filtration, showing strong buffering performance. Filtration times for 500 ml of water ranged between 1 minute 34 seconds and 3 minutes 55 seconds, reflecting practical usability. While there is opportunity to enhance speed, the results confirm consistent performance in processing chemically diverse water samples.

Table 4 Water quality test results before and after filtration

Substance	pH Before	Time	pH After
Small Lemon	3.6	1 min 34 sec	6.51
30 grams of tea	4.8	2 min 03 sec	6.88
30 grams of salt	7.2	3 min 21 sec	6.95
30 grams of baking soda	8.4	3 min 55 sec	7.43

As seen in Figure 6, the system features a graphical user interface (GUI) that provides real-time monitoring of water quality and operational parameters. Users can view pH, TDS, temperature, water level, and battery status, along with pump activity. The interface is designed to be intuitive and accessible from any Wi-Fi-enabled device, offering a seamless user experience without requiring technical knowledge or internet access. The interface becomes accessible within approximately 30 seconds of powering on the system, ensuring a quick and responsive startup for field use.

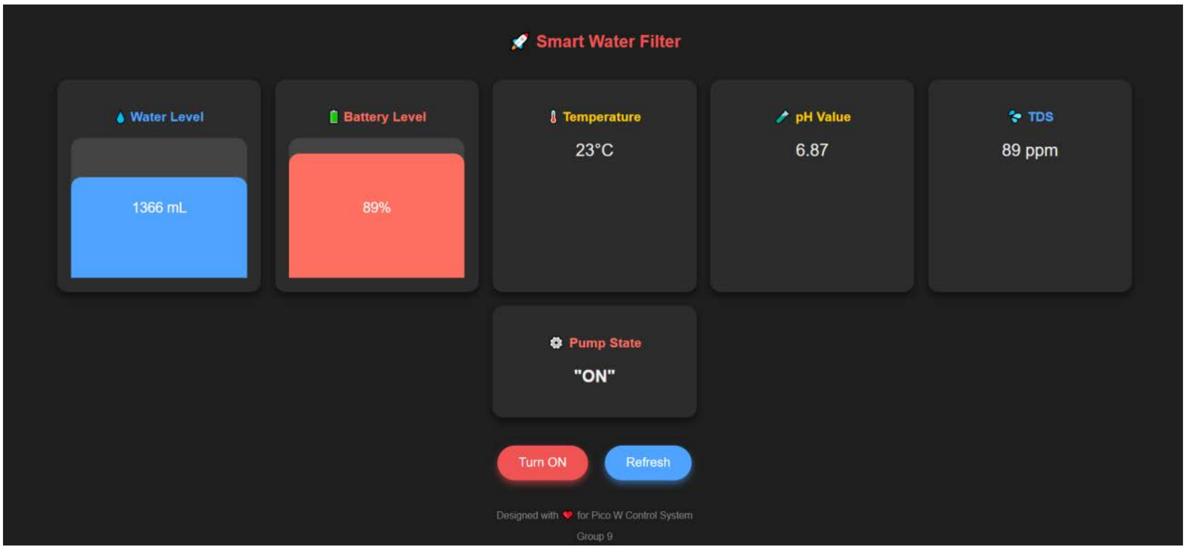

Figure 6. User interface

At the configured default update interval of one transmission per minute, the system sends approximately 10.5 kilobytes of data with each request. This includes all HTTP headers, as well as the complete HTML body containing layout, styles, and repeated interface elements. In contrast, the actual sensor data represents only around 50 bytes, meaning over 99% of the transmitted content is unrelated to the core data. Additional traffic may be generated in response to user interaction, such as page reloads or pump control commands, but these events are infrequent and considered negligible for this estimation. While the total data transmitted per minute remains modest and suitable for local offline use, the ratio of meaningful data to total transfer is highly inefficient. This trade-off was considered acceptable for the initial prototype due to its simplicity, cross-platform accessibility, and lack of reliance on external infrastructure. However, by restructuring the communication process to transmit only raw sensor data in a lightweight format such as JSON, the amount of data transmitted per request could be reduced by over 98%, offering a substantial opportunity for future optimization. This behavior is quantitatively detailed in Table 5.

Table 5 Compact data transfer

Item	Data Transmitted
Sensor data (6 floats + 1 bool)	50 bytes
HTML + HTTP headers (per request)	10.5 KB
Update frequency (default)	Every 60 seconds
Data per minute (1 user)	10.5 KB

Based on the assumption that the system uses a single solar panel with a surface area of 136 mm by 110 mm, a cell efficiency of 19.5%, and is operated in Perlis, Malaysia—an area receiving approximately 5 peak sun hours per day—the daily energy generation can be estimated using the expression:

$$E = \eta \times A \times G \times H \times L \quad (1)$$

where η is the panel efficiency (19.5%), A is the panel area in square meters (0.01496 m^2), G is the standard solar irradiance (1000 W/m^2), H is the average peak sun hours (5 h), and L is the estimated system efficiency after accounting for orientation and charging losses (approximately 76.5%). Using this formulation, the expected daily usable energy is approximately 11.2 watt-hours. This value represents the upper bound of energy available for battery charging and system operation under typical sunlight conditions and provides the basis for evaluating the system's daily energy balance relative to consumption.

Based on the assumption that the system operates for one hour per day, the total energy consumption is estimated as summarized in Table 6. During this period, the user is assumed to filter one liter of water daily, with the filtration process for 500 milliliters taking approximately 2 minutes and 3 seconds, and an additional 1 minute required for dispensing. Under these conditions, the Raspberry Pi Pico W and its Wi-Fi module consume approximately 0.75 watt-hours. The sensors and OLED display, which remain active throughout the session, contribute an additional 0.26 watt-hours. The combined operation of the filtration and dispensing pumps, along with the relay, accounts for 0.7 watt-hours over a total runtime of seven minutes. This brings the total daily energy consumption during active use to approximately 1.71 watt-hours. This value reflects a controlled and predictable energy profile suitable for low-duty applications, such as portable or off-grid deployments, and is appropriate for this early-stage prototype.

As shown in the table, the system consumes approximately 1.71 watt-hours of energy per day, while the estimated energy generated by the solar panel under typical conditions is 11.2 watt-hours. This indicates that the energy produced significantly exceeds the system's daily consumption, providing a comfortable surplus to support consistent operation and battery charging.

Table 6 Power consumption

Component Group	Estimated Duration	Total Energy (Wh)
Pico W + Wi-Fi	1 hour	0.75 Wh
All Sensors + OLED	1 hour	0.26 Wh
Pumps + Relay	7 minutes	0.7 Wh
Energy Consumed	1.71 Wh	
Energy Generated	11.2 Wh	

The portability of the system was assessed across five core criteria: physical design, power autonomy, setup and operation, environmental resilience, and modularity and maintenance. Each aspect was rated on a scale from 1 to 5 on Table 7 to reflect its effectiveness in supporting mobile, off-grid use. In terms of physical design, the system maintains a compact footprint and moderate weight, with prior measurements indicating a manageable profile for personal transport. The inclusion of a built-in side handle further enhances usability by allowing the device to be comfortably carried by hand. These attributes align well with the intended use in field environments, justifying a high rating in this category.

Power autonomy was evaluated based on the system's ability to function independently over extended periods without external power input. Under typical usage conditions, the system can operate for over 19 consecutive days on a single full battery charge. When combined with consistent daily solar input, this autonomy ensures dependable operation in remote or off-grid environments. The system's energy profile supports its intended use case and justifies a top rating in this category of the portability evaluation.

The system is designed for quick and straightforward deployment, requiring no tools or technical expertise to operate. Upon powering the unit, all core components including the Wi-Fi access point, sensor suite, and graphical user interface initialize automatically and are fully ready within approximately 30 seconds. Users can interact with the system via a standard web browser on any Wi-Fi-enabled device, eliminating the need for dedicated applications or internet connectivity. This intuitive, self-contained setup process enhances user accessibility and supports rapid use in field conditions, earning a top rating in this category of the portability evaluation.

Environmental resilience was evaluated in terms of weather, heat, and handling conditions. The system offers basic protection against light rain and splashes but is not sealed against heavy water exposure or dust. PLA and PVC materials are suitable for short-term outdoor use but may deform under prolonged heat. Mechanical protection is limited, with some internal components vulnerable to disconnection. However, the system performed reliably during field testing in Malaysia's hot and humid climate. Overall, this category receives a moderate rating, with room for future improvement.

Modularity and maintenance were evaluated based on the ease of accessing, replacing, or servicing key components in the field. While the battery is easily accessible and can be replaced without specialized tools, most other components including sensors, pumps, and internal wiring are not designed for user-level replacement. The system lacks modular connectors or a service-friendly layout, making repairs difficult for non-technical users. In the event of malfunction or component failure, disassembly and technical intervention would likely be required. Given these limitations, this category receives a low rating in the overall portability evaluation.

Table 7 Portability evaluation

Parameter	Rating (1–5)	Remarks
1. Physical Design		
Dimensions	5	Compact and manageable (41 × 33 × 31 cm)
Weight	4	Portable for most users (5–8.4 kg)
Carrying method	4	Side handle included, comfortable grip
2. Power Autonomy		
Battery capacity	5	33.3 Wh supports up to ~19.5 days of use
Daily energy consumption	5	low (1.71 Wh/day)
Solar charging capability	4	Sufficient for daily use, ~11.2 Wh/day
3. Setup & Operation		
User interface simplicity	5	Intuitive browser interface, no app needed

Deployment time	5	Fast startup (~30 sec)
Tool requirement	5	No tools required
4. Environmental Resilience		
Water resistance	3	Splash-resistant only; not sealed
Dust protection	2	Open to dust; no filters or sealing
Heat/sunlight tolerance	3	Acceptable short-term; PLA can soften in heat
Impact/shock resistance	3	Vulnerable to damage
5. Modularity & Maintenance		
Battery replacement	4	Easy to replace
Component replacement	2	Difficult for non-technical users
Repairability	2	Not designed for maintenance or disassembly

4. CONCLUSION

The Smart Portable Water Purification System offers an effective and user-friendly solution for providing clean drinking water in off-grid and temporary settings. With its multi-stage filtration, the system removes a wide range of contaminants. Real-time monitoring via pH and TDS sensors, combined with a solar-powered supply and IoT-based control through the Raspberry Pi Pico W, enables autonomous operation. A built-in graphical interface accessible over Wi-Fi without requiring internet access. While the prototype meets its primary goals, several improvements are proposed for future development. These include creating a more compact and rugged design, improving solar charging efficiency, and increasing filtration speed. Expanding the sensing module with additional parameters like turbidity and microbial detection, along with switching to more energy-efficient communication protocols and better data handling, could further enhance system reliability. Additionally, a custom mobile app could offer more advanced control, alerts, and analytics to improve the overall user experience.

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