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HydroClear: Saltwater Sterilization

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Abstract

Access to safe drinking water remains a critical challenge, particularly in regions where saline water is abundant but unsuitable for direct consumption. Conventional desalination systems often involve high energy consumption, complex infrastructure, and losses due to DC–AC power conversion, limiting their use in small-scale applications. This paper presents HydroClear, a solar-powered water treatment system that converts saltwater into sterilized water using a controlled evaporation–condensation process. The system utilizes a 12 V DC immersion heater powered directly by a photovoltaic panel, eliminating inverter losses and improving efficiency.Automation is implemented using an STM32F401RE Nucleo microcontroller, which operates based on real-time sensor monitoring of temperature, humidity, and water quality (TDS). The system ensures controlled heating, effective condensation, and reliable output with minimal human intervention. The proposed design demonstrates a simple, cost-effective, and energy-efficient solution for small-scale water sterilization, making it suitable for remote and sustainable applications.

Keywords: Solar water treatment, DC heating, sterilized water, evaporation-condensation, STM32 microcontroller, renewable energy systems.

1. Introduction

The availability of safe drinking water has become a growing global concern due to rapid population growth, industrialization, and the contamination of natural water sources. In many coastal and remote regions, saline or polluted water is readily available but unsuitable for direct consumption. Although large-scale desalination plants offer effective solutions, their high energy requirements, complex infrastructure, and operational costs make them impractical for decentralized and small-scale applications.

Thermal water treatment based on evaporation and condensation remains one of the most reliable purification methods, as it effectively removes salts, suspended particles, and biological contaminants. However, the water obtained through condensation is largely free from dissolved minerals and is therefore classified as sterilized water rather than mineral-balanced drinking water. Despite this limitation, sterilized water is widely used in domestic, medical, laboratory, and emergency applications where water safety is of primary importance.

Solar energy provides a sustainable and environmentally friendly power source for thermal water treatment systems. Conventional solar desalination setups often utilize photovoltaic panels in combination with DC–

AC inverters to operate AC heating elements, resulting in increased power losses and system complexity. In contrast, direct DC-powered heating offers a more efficient and cost-effective alternative, particularly for low- to medium-power applications.

This paper presents HydroClear, a solar-powered water sterilization system that utilizes a 12 V DC immersion heater directly powered by a photovoltaic panel to achieve controlled evaporation of saline water. To ensure stable and efficient operation, a DC–DC buck converter is incorporated to regulate and distribute the required voltage levels for auxiliary components and control circuitry. This approach simplifies the power architecture while improving overall system efficiency.

System automation and monitoring are implemented using an STM32F401RE Nucleo microcontroller, which processes real-time data from temperature, humidity, and total dissolved solids (TDS) sensors. Two temperature sensors are used to monitor the conditions of the saline water tank and the condensate collection tank, ensuring safe and controlled heating. A humidity sensor assists in evaluating vapor generation and condensation performance, while the TDS sensor is used to assess the quality of the collected sterilized water.

Additional components, including a solenoid valve for water flow control, relay-based switching for heater operation, and a Hall effect sensor for system state detection, enable reliable and autonomous system functionality. The integration of these components with a microcontroller-based control strategy ensures minimal human intervention and enhances system reliability.

The proposed system emphasizes energy efficiency, simplified power design, and sensor-based automation, making HydroClear suitable for educational research, experimental validation, and small-scale solar water sterilization applications.

2. LITERATURE SURVEY

Various desalination and water purification techniques have been developed to address the growing challenge of water scarcity, particularly in regions where saline water is readily available but unsuitable for direct consumption. These methods aim to remove dissolved salts and impurities; however, they often involve trade-offs between efficiency, cost, and system complexity.

A desalination approach based on electrodialysis utilizes ion-exchange membranes and an external electric field to separate dissolved salts from water. The system demonstrates effective ion removal under controlled conditions and allows optimization through simulation of ion transport behavior. However, the use of specialized membranes increases system cost and maintenance requirements, while issues such as membrane fouling and degradation reduce long-term efficiency, limiting its applicability in low-cost and small-scale systems. [1]

To enhance monitoring and control, smart desalination architectures have been explored. A cloud and IoT-based system enables real-time monitoring of parameters such as water quality, temperature, and flow rate, improving operational efficiency through remote access and data-driven analysis. Despite these advantages, the integration of cloud infrastructure and communication modules increases system complexity and cost. Additionally, dependency on internet connectivity makes such systems less suitable for remote or off-grid environments. [2]

Solar-based desalination methods have also been widely investigated to improve sustainability. A photovoltaic-driven thermal desalination system utilizes solar energy to heat saline water, enabling evaporation and condensation for purification. While this approach is environmentally friendly and reduces dependence on conventional energy sources, its performance is highly dependent on solar intensity. The heating process is relatively slow, and the absence of effective automation limits system reliability and output consistency. [3]

Further improvements in thermal efficiency have been achieved through optical concentration techniques. A system using lenses or mirrors to concentrate solar radiation increases the temperature of saline water and enhances evaporation rates. Although this method improves efficiency, it introduces additional complexity due to the need for precise alignment and maintenance of optical components, which increases cost and reduces system robustness. [4]

Decentralized desalination solutions have also been explored to address water scarcity in remote areas. A micro-scale desalination system utilizing distributed renewable energy sources focuses on modularity and adaptability. While this approach supports off-grid applications, fluctuations in energy availability can affect system performance. The integration of multiple subsystems further increases complexity and may impact reliability in practical implementations. [5]

More advanced interdisciplinary approaches have also emerged. A desalination method combining solar energy with genetically modified microorganisms utilizes halorhodopsin-expressing E. coli for light-driven ion transport. Although this method introduces an innovative mechanism for desalination and energy generation, it involves complex biological processes requiring controlled conditions. Challenges related to scalability, stability, and implementation cost limit its practical application. [6]

In addition to individual system designs, broader analyses of desalination technologies have also been presented through review studies. Membrane-based desalination techniques such as reverse osmosis and nanofiltration are widely used due to their high salt rejection efficiency and scalability, enabling large-scale purified water production. However, these systems require high operating pressure, significant electrical energy, and periodic membrane replacement due to fouling and scaling, increasing operational cost and limiting feasibility for small-scale applications. [7]

A comprehensive evaluation of desalination as a sustainable water source has analyzed multiple techniques including thermal distillation, reverse osmosis, and hybrid systems. While desalination plays a crucial role in addressing global water scarcity, challenges such as high energy consumption, environmental concerns related to brine disposal, and the need for efficient waste management systems restrict large-scale adoption in environmentally sensitive and resource-limited regions. [8]

Further insights into various desalination methods show that techniques such as distillation, electrodialysis, and membrane filtration offer specific advantages depending on operating conditions and water quality requirements. However, no single method provides a complete solution, as trade-offs exist between efficiency, cost, and system complexity, highlighting the need for simpler and more adaptable approaches. [9]

A review on desalination plant production and brine management highlights operational challenges and environmental impacts associated with large-scale systems. Concentrated brine discharge can harm marine ecosystems, while issues such as scaling, corrosion, and fouling affect efficiency and increase maintenance requirements. These challenges emphasize the need for more sustainable and environmentally friendly system designs. [10]

Advancements in desalination processes and hybrid energy systems demonstrate that integrating renewable energy sources such as solar power can improve sustainability and reduce dependence on conventional energy. However, combining multiple subsystems increases design complexity and requires efficient energy management to ensure stable operation. [11]

Recent developments in desalination technologies focus on improving efficiency and reducing environmental impact through innovative techniques. Despite these advancements, challenges related to high initial cost, system reliability, and long-term operational stability continue to limit widespread implementation. [12]

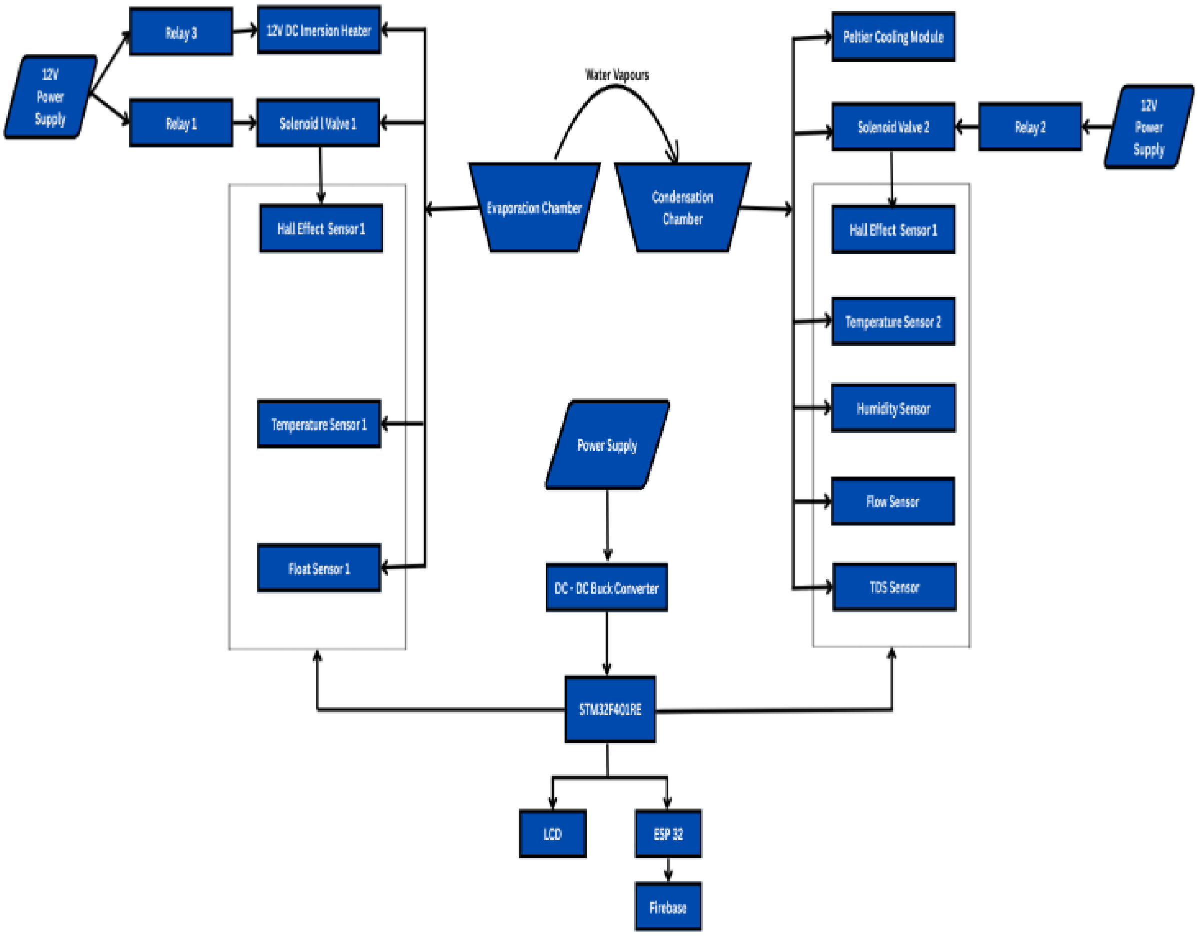

Figure 1: Block Diagram

Emerging desalination approaches involving advanced materials and alternative energy-driven processes show promising results in controlled environments. However, these methods are still in developmental stages and require further validation before practical deployment. [13]

A comprehensive review of desalination technologies, environmental impacts, and future perspectives emphasizes the global need for sustainable water treatment solutions. Although significant progress has been made, achieving a balance between efficiency, cost-effectiveness, and environmental sustainability remains a major challenge. [14]

Further studies on desalination performance and process optimization highlight that improving heat transfer, optimizing system design, and integrating renewable energy can enhance efficiency. However, system complexity, high energy requirements, and operational costs remain key barriers, reinforcing the need for simplified and energy-efficient solutions for small-scale applications. [15]

3. PROPOSED SYSTEM

The proposed system, HydroClear, is a solar-powered water sterilization unit designed to convert saline water into sterilized water using a controlled evaporation–condensation process. The system operates on a 12 V DC power supply, which is directly obtained from a photovoltaic panel, eliminating the need for DC–AC conversion and thereby reducing energy losses. A 12 V DC immersion heater is used to heat the saline water, causing it to evaporate. The generated water vapor is then condensed in a separate chamber to produce sterilized water, leaving behind salts and impurities in the source tank.

To ensure efficient and safe operation, the system incorporates a DC–DC buck converter to provide regulated voltage levels for auxiliary components such as sensors and control circuitry. The entire system is controlled using an STM32F401RE Nucleo microcontroller, which processes real-time data from multiple sensors. Two temperature sensors are used to monitor the conditions of the saline water tank and the condensate collection tank, ensuring controlled heating and preventing overheating. A humidity sensor is used to assess vapor formation and condensation efficiency, while a TDS sensor is used to evaluate the quality of the collected sterilized water.

Automation is achieved through the integration of a solenoid valve, relay-based heater control, and a Hall effect sensor for system state detection. The microcontroller continuously monitors sensor inputs and controls the operation of the heater and valve based on predefined conditions. In case of abnormal conditions such as high temperature or low water level, the system automatically shuts down the heater to ensure safety. This design provides a simple, energy-efficient, and low-cost solution for small-scale water sterilization, making it suitable for educational, experimental, and decentralized applications

4. METHODOLOGY

The HydroClear system is designed as a solar-powered, automated water sterilization unit based on the controlled evaporation–condensation principle. The complete operational workflow of the system is illustrated in Figure 2.

As shown in Figure 2, the process begins with system initialization, where the STM32F401RE microcontroller activates all sensors and checks system readiness. The system first performs a water level check in the primary tank using a level sensor. If the water level is below the predefined threshold, the controller activates the inlet solenoid valve, allowing water to enter the tank. Once the desired level is reached, the valve is automatically closed.

After ensuring sufficient water level, the system proceeds to the heating stage. A relay is triggered to switch ON the 12 V DC immersion heater, which increases the temperature of the saline water. Temperature sensors continuously monitor the system during this process. As the temperature rises, evaporation begins, generating water vapor while leaving behind salts and impurities.

The vapor is then directed toward the cooling and condensation unit, where a Peltier module enhances heat dissipation and promotes condensation. A humidity sensor monitors vapor presence and condensation efficiency. The condensed vapor is collected as purified water in the output tank, as indicated in Figure 1.

The system then evaluates whether the temperature exceeds a predefined threshold. If the temperature crosses this limit, the heater is immediately turned OFF, and an alert is sent via the ESP module to Firebase, generating a mobile notification. If the temperature remains within safe limits, the system continues the heating, evaporation, and condensation processes.

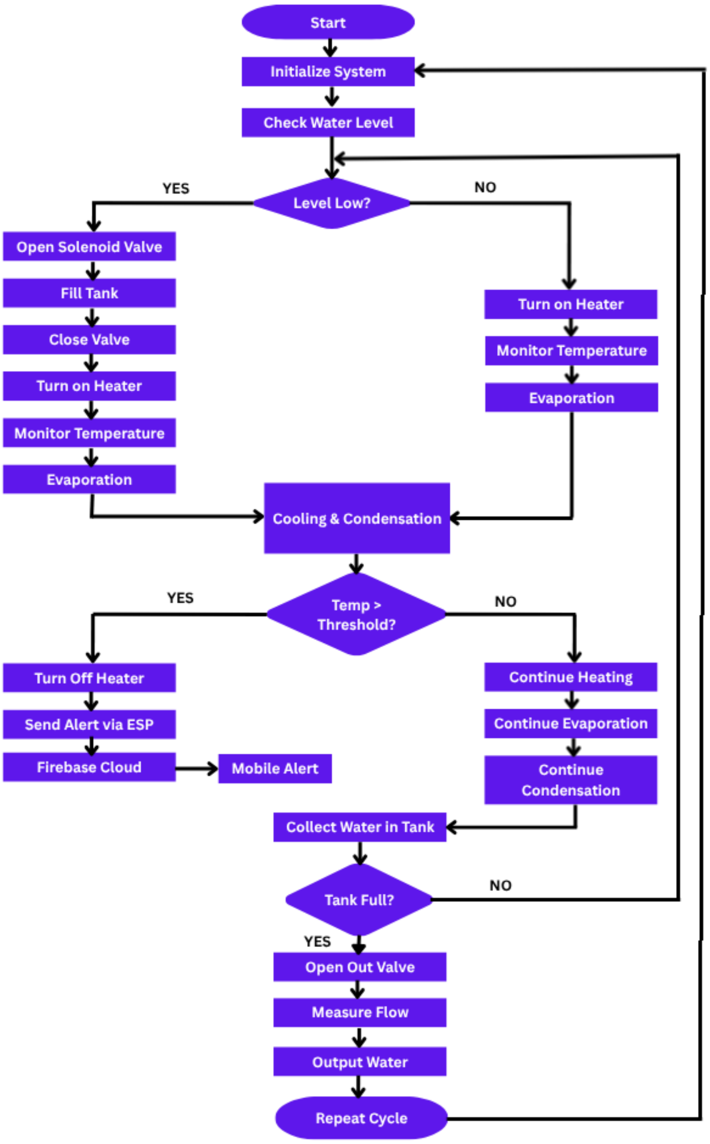

Figure 2 Flowchart

Once sufficient water is collected, the system checks whether the output tank is full. If the tank reaches its maximum level, the outlet solenoid valve is activated to release water. A flow sensor measures the quantity of water delivered. After the discharge process, the system resets and returns to the initial state, continuing the cycle as shown in Figure 1.

Simultaneously, as evaporation reduces the water level in the primary tank, the system continuously monitors it. When the level drops below the threshold, the heater is turned OFF, and the inlet valve is reactivated to refill the tank, ensuring uninterrupted operation.

Thus, as depicted in Figure 1, the HydroClear system operates as a closed-loop automated system, integrating sensing, control, heating, purification, and output mechanisms to achieve efficient, safe, and continuous water sterilization.

The HydroClear system operates as a solar-powered, fully automated water sterilization unit based on the controlled evaporation–condensation principle. The system is powered using a 12 V photovoltaic panel, and a stable operating voltage for control and sensing components is maintained using a DC–DC buck converter. The process begins with the primary tank, where saline water is stored. A level sensor continuously monitors the water level, and when the level falls below a predefined threshold, a solenoid valve is activated to allow water to enter the tank. Once the required level is reached, the valve is turned OFF automatically to prevent overflow. At this stage, the control system activates a relay, which switches ON the 12 V DC immersion heater. The heater raises the temperature of the saline water, initiating the evaporation process. Two temperature sensors continuously monitor the temperature of the primary tank and the condensation chamber to ensure safe and efficient operation.

As the temperature increases, water begins to evaporate, and the generated vapor rises while leaving behind salts, dissolved solids, and other impurities in the primary tank. This vapor is directed into a secondary chamber designed for condensation. A Peltier cooling module is employed in this chamber to actively reduce the temperature, thereby enhancing the condensation rate compared to passive cooling methods. A humidity sensor is installed in the secondary chamber to monitor vapor concentration and assess condensation effectiveness. As the vapor cools, it condenses into liquid form, producing sterilized water, which is then collected in the output tank. A TDS (Total Dissolved Solids) sensor in the output tank evaluates the purity of the collected water, ensuring that the dissolved salt content is significantly reduced.

To manage water output, a second level sensor is used in the output tank. When the water level reaches a predefined limit, a second solenoid valve is activated to allow the sterilized water to flow out of the system. A flow sensor is installed at the outlet to measure the quantity of water being delivered, enabling performance monitoring. Additionally, a Hall effect sensor is integrated to monitor the operational status of valves and ensure proper control logic execution. As evaporation continues, the water level in the primary tank gradually decreases. When it falls below the threshold, the system automatically turns OFF the heater via the relay and reactivates the inlet solenoid valve to refill the tank. This closed-loop control mechanism allows continuous operation with minimal human intervention, ensuring efficient, safe, and reliable water sterilization.

5. RESULTS AND DISCUSSIONS

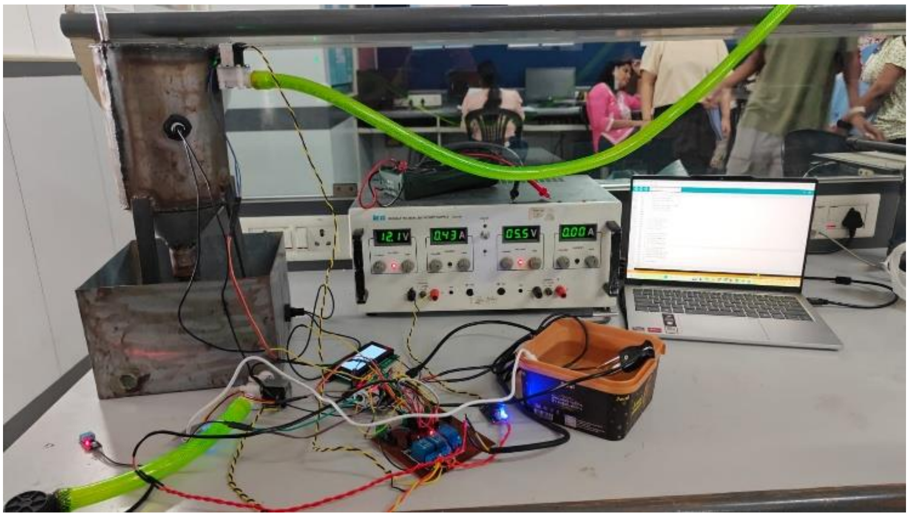

Figure 3 Hardware setup

The HydroClear system was designed and experimentally evaluated as an automated water sterilization unit based on the evaporation–condensation principle. The complete experimental setup used for validation is shown in Figure. 3.

The system demonstrated successful integration of hardware components including the STM32 microcontroller, sensors, relay modules, and communication interfaces. During operation, saline water was heated using a 12 V DC immersion heater, initiating the evaporation process. The generated water vapor was directed toward the condensation chamber for cooling and collection.

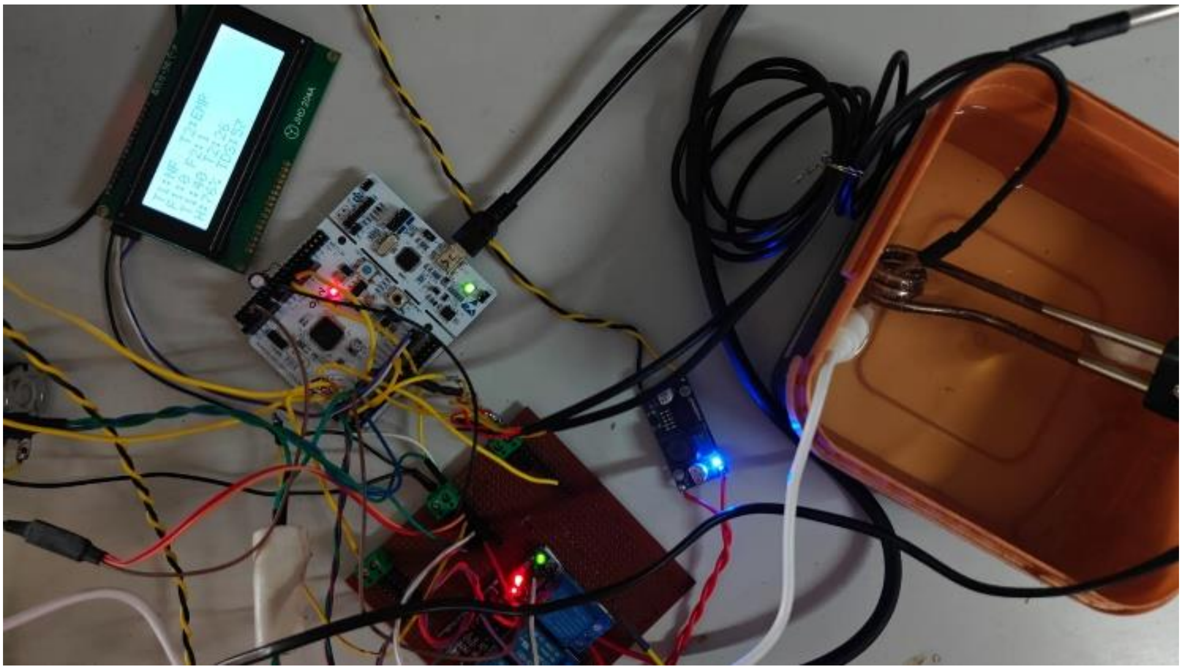

Figure 4 Heating Trial

Temperature sensors placed in both chambers continuously monitored thermal conditions and ensured controlled heating. The float sensor enabled automatic water level management, while the relay-controlled solenoid valves regulated water inflow and outflow. The LCD display provided real-time visualization of parameters such as temperature, flow rate, and system status.

The heating trial, as shown in Figure 4, confirmed that the system was capable of increasing water temperature effectively and initiating vapor formation. The sensor readings displayed on the LCD validated proper functioning of the sensing and control mechanisms. The microcontroller successfully executed the programmed logic for heater control based on temperature thresholds.

Additionally, the integration of IoT functionality enabled real-time monitoring of system parameters through Firebase. Temperature data and alert conditions were transmitted to the cloud, demonstrating reliable communication between the hardware system and the remote database.

The TDS sensor readings indicated a reduction in dissolved solids in the processed water, suggesting the effectiveness of the desalination process. However, the overall efficiency of condensation was observed to be limited due to practical constraints such as heat loss and limited cooling capacity of the Peltier module.

Despite these limitations, the system successfully validated the working principle of automated water purification using thermal methods. The results confirm that the proposed system is capable of performing controlled evaporation, basic condensation, and real-time monitoring, making it a feasible solution for small-scale water treatment applications.

6. CONCLUSION AND FUTURE SCOPE

In The HydroClear system presents an automated approach for water sterilization based on the evaporation–condensation principle integrated with embedded control and IoT-based monitoring. The system was successfully designed, implemented, and experimentally evaluated using a combination of sensors, relay-based control, and communication modules.

The results demonstrate that the system is capable of controlled heating of saline water using a 12 V DC immersion heater, thereby initiating the evaporation process. The use of temperature and level sensors ensured proper monitoring and automation of system operations, while the microcontroller effectively controlled the heater and solenoid valves based on predefined conditions. The LCD display provided real-time feedback of system parameters, enhancing usability.

In addition, the integration of the ESP module with Firebase enabled real-time remote monitoring of system data. The system successfully transmitted temperature readings and alert conditions to the cloud, demonstrating reliable IoT functionality. The TDS sensor readings indicated a reduction in dissolved solids, validating the feasibility of the desalination process.

However, the overall efficiency of the system is affected by practical limitations such as heat loss and limited cooling capability of the Peltier module used in the condensation stage. Despite these constraints, the system successfully validates the concept of automated water purification using thermal methods combined with smart monitoring.

In future, the system can be significantly improved by enhancing the condensation mechanism using more efficient cooling techniques such as heat exchangers. The integration of renewable energy sources like solar power can make the system more sustainable and suitable for remote applications. Further improvements can include better thermal insulation, advanced control algorithms, and the development of a user-friendly mobile or web-based interface for monitoring and control.

With these enhancements, the HydroClear system has the potential to evolve into a more efficient, scalable, and practically deployable solution for water purification and management.

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