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Smart Clove Oil Distillation System using IoT and Ultrasonic Sensors

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Abstract

Traditional clove essential oil distillation remains inefficient due to manual labor dependency, imprecise oil-water separation, and inconsistent product quality. Addressing these limitations, this study aims to design and develop a smart, Internet of Things (IoT)-based system named AquaClove to automate and optimize the distillation process. The system integrates an ESP32 microcontroller, ultrasonic sensors, and solenoid valves, enabling precise fluid level detection and automated oil-water separation. Using the Arduino IoT Cloud, the system supports real-time monitoring and remote control, enhancing operational transparency and scalability. results indicate that the system achieved a 32% reduction in total distillation time (from 4.2 to 2.9 hours), 66.7% reduction in labor requirements (from 3 to 1 personnel), and 66.7% reduction in oil loss per 10-liter batch (from 0.6 L to 0.2 L). The ultrasonic sensors consistently detected liquid levels with an average measurement deviation of less than ±2 mm, while solenoid valves responded within 0.8 seconds of command input. These outcomes demonstrate significant improvements in process efficiency, separation precision, and system responsiveness. Furthermore, the modular container design promotes gravity-assisted separation, enhancing energy efficiency and reducing mechanical complexity. The remote monitoring feature allows users to access real-time data on fluid levels and system status, ensuring reliable operation with minimal manual supervision. AquaClove thus demonstrates how integrating ultrasonic sensing and IoT technologies can modernize traditional agricultural processes. This study contributes a scalable and sustainable solution to the essential oil industry, particularly in small- and medium-scale clove oil production.

Keywords: clove essential oil, oil-water separation, ultrasonic sensor technology, automated distillation system, internet-based remote monitoring

1 Introduction

Clove essential oil (Syzygium aromaticum) has long been valued for its antimicrobial, antioxidant, and anti-inflammatory properties, supporting its widespread use in food, pharmaceutical, and cosmetic industries [1][2][3][4][5][6]. One of its primary bioactive compounds, eugenol, plays a major role in increasing the oil's functional value, making it an important raw material across industrial applications [7][8]. However, clove oil production remains predominantly traditional and manual, particularly in small-scale operations, resulting in several limitations such as low production efficiency, inconsistent oil quality, and labor dependency [10][11][19].

The oil-water separation phase is especially problematic due to the difficulty in precisely distinguishing clove oil from condensate water. Inefficient separation not only leads to product loss but also hampers the scalability and hygiene of the process [1][10]. Therefore, innovations are needed to improve this stage, particularly through the use of appropriate sensing and automation technologies.

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Recent advances in ultrasonic sensor technology have demonstrated potential for non-invasive, real-time liquid level detection, offering improved control over separation processes in fluid-based systems [9][13][14][15]. Likewise, the development of low-cost microcontrollers, such as ESP32, and their seamless integration with Internet of Things (IoT) platforms allow automated systems to be remotely monitored and controlled [16][17][18][20][22][23]. Despite these advancements, their application in the clove oil industry remains limited.

The problem addressed in this study is the absence of an automated system capable of accurately separating oil from water during the distillation process. Without such a system, producers face persistent inefficiencies, labor costs, and inconsistent product quality. Solving this challenge through the integration of sensor-based control and real-time remote monitoring would improve operational productivity and sustainability [19][20][23][24].

This study aims to develop AquaClove, an IoT-based automated system that utilizes ultrasonic sensors, solenoid valves, and an ESP32 microcontroller integrated with the Arduino IoT Cloud platform. The goal is to optimize the clove oil distillation process by reducing manual intervention, improving separation accuracy, and enhancing production efficiency. The significance of this research lies in its contribution to the modernization of traditional essential oil production systems through sustainable, low-cost automation, with the potential for broader application in other agricultural industries [25][26][27].

2. Literature Review

Essential oil extraction technology has undergone significant transformation with the integration of advanced sensing and automation systems. Numerous studies have highlighted the critical role of clove essential oil, primarily due to its eugenol content, which has applications in pharmacology, food preservation, and cosmetics [2][3][7]. However, challenges persist in optimizing the distillation process, particularly in the precise separation of clove oil from water, which remains largely manual and prone to quality inconsistencies [8][10][11].

To address these limitations, researchers have explored various innovations, including the application of ultrasonic technology to improve fluid-level detection and separation precision. For instance, Yu et al. [13] and Ni et al. [15] demonstrated the effectiveness of ultrasonic sensors in non-invasive liquid detection and condition monitoring. While promising, these studies remained focused on general fluid systems and did not propose a complete framework for automated separation in distillation settings. Our system builds upon these findings by incorporating ultrasonic sensors not just for measurement, but as a decision-making input for real-time actuation.

In parallel, IoT-based automation systems have been shown to improve monitoring and control processes across domains. Talbi et al. [18] and Nur-A-Alam et al. [20] reported significant enhancements in responsiveness and data accessibility using IoT for real-time telemetry. However, few studies have contextualized this potential for small-scale post-harvest processing systems. Unlike existing approaches that either focused on remote sensing or environmental monitoring [22][25], our system integrates IoT to directly influence the operational state of physical actuators namely solenoid valves based on sensor input, thereby enabling automated, closed-loop control in real-world distillation scenarios.

Moreover, solenoid valves have been explored for their suitability in precise fluid regulation [24], but integration with IoT and sensing technologies remains underutilized in essential oil applications. The AquaClove system distinguishes itself by combining these three technologies ultrasonic sensors, solenoid valve actuation, and cloud-based monitoring into a unified, scalable platform. This approach bridges the gap in previous research by offering a modular system specifically designed for the oil-water separation stage in clove oil distillation.

In summary, while prior works provide foundational insights into individual components, our study is the first to implement and validate a comprehensive system that synchronizes sensor input, actuator response, and remote monitoring for essential oil processing. This direct linkage between the literature and our system design enhances the contextual relevance and demonstrates the practical feasibility of modernizing traditional distillation practices through IoT integration.

3. Research Method

This research adopts an experimental approach focusing on the design, implementation, and evaluation of an automated clove oil distillation system named AquaClove. The study was conducted

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at the Technology Laboratory of Universitas Muslim Indonesia, where hardware integration, programming, and system testing took place. The main object of this research is the distillation process of clove essential oil, specifically the oil-water separation stage, which is optimized through automation.

The primary materials used include fresh clove leaves and water, which serve as the base mixture for distillation. Key instruments employed in the study are ultrasonic sensors for liquid level detection, solenoid valves for fluid control, and the ESP32 microcontroller as the processing unit. Supporting devices include relay modules, a step-up voltage module, and the Arduino IoT Cloud platform for real-time data monitoring and remote control. The integration and deployment of these components were executed using the Arduino IDE, allowing synchronization between sensors, actuators, and cloud interfaces.

The development process was structured into several phases: component selection and assembly, system programming, integration, and performance validation. The system's architecture is modular, consisting of three primary containers: the upper processing chamber, middle filtration unit, and lower separation container. This configuration promotes gravity-assisted flow and supports separation efficiency.

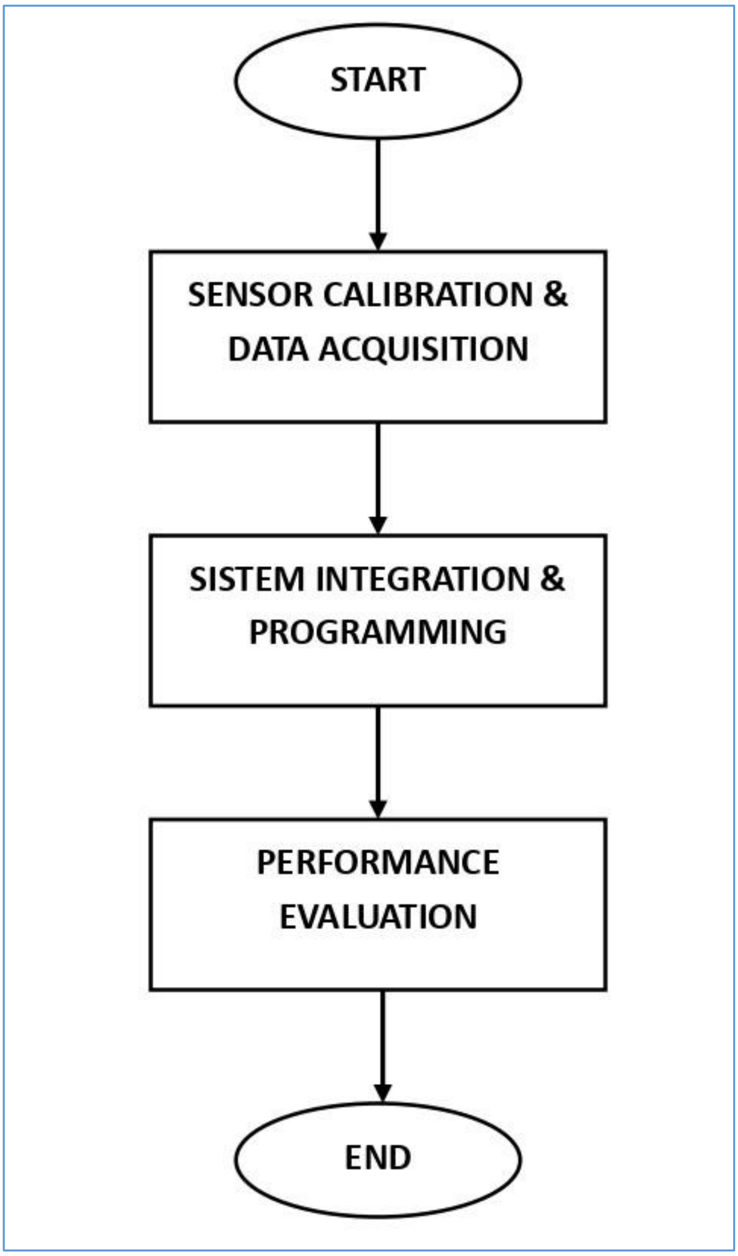

Figure 1. Research methodology

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The methodology employed in this study is structured into three main activities, each representing a critical phase in the development and validation of the AquaClove system. These activities are illustrated in the system flowchart in Figure 1 and further supported by the physical design in Figure 2.

First, the sensor calibration and data acquisition phase involved configuring the ultrasonic sensor to accurately detect fluid levels within the separation chamber. Multiple tests were conducted using known liquid volumes, with sensor readings compared against manual measurements to establish baseline accuracy and threshold values for system response.

Second, the system integration and programming phase focused on the hardware-software interaction. Components such as the ESP32 microcontroller, solenoid valve, and relay module were physically assembled and programmed via the Arduino IDE. Real-time data transmission was enabled through the Arduino IoT Cloud, allowing bidirectional communication for monitoring and control.

Third, the performance evaluation phase assessed the system's responsiveness, accuracy, and efficiency. Metrics such as sensor deviation, valve actuation time, and reduction in labor and oil loss were measured across multiple trials. The system's capability to operate autonomously and reliably under various fluid levels and environmental conditions was also validated.

These three stages collectively ensured that the AquaClove system met the objectives of automation, precision, and scalability for clove oil distillation processes.

Operational variables in this study include: (1) sensor accuracy, defined as the ability of ultrasonic sensors to detect fluid levels with minimal deviation; (2) valve responsiveness, defined as the reaction time and consistency of solenoid valves in executing control commands; and (3) process efficiency, measured by reductions in manual intervention and processing time.

Data were collected through repeated trials of the distillation process under varying volumes and durations. Sensor output, valve actuation time, and IoT data transmission logs were recorded and analyzed. Data collection techniques included real-time observation, system log exports, and manual cross-validation using graduated measuring tools. Each trial was documented with precise timing and volume records.

Data analysis was performed quantitatively to evaluate sensor deviation, actuation delay, and efficiency metrics. Comparative analysis was used to assess system performance before and after optimization. The results were interpreted to determine the reliability, scalability, and practicality of the AquaClove system in real-world clove oil production

4. Results and Analysis

The AquaClove system underwent a series of performance evaluations corresponding to the stages defined in the methodology. Each performance parameter was tested to ensure the accuracy, responsiveness, and efficiency of the automated distillation process.

To help visualize the functionality of the AquaClove system, this section presents two key diagrams that illustrate the operational logic and physical structure of the system. Figure 2 shows the system flow diagram, outlining the sequence of operations from sensor readings to actuator control. Meanwhile, Figure 3 details the physical modular design of the system, highlighting the placement of components such as the ultrasonic sensor, ESP32 microcontroller, and solenoid valve. These diagrams are essential for understanding how sensor input and cloud-based decision-making coordinate the distillation process.

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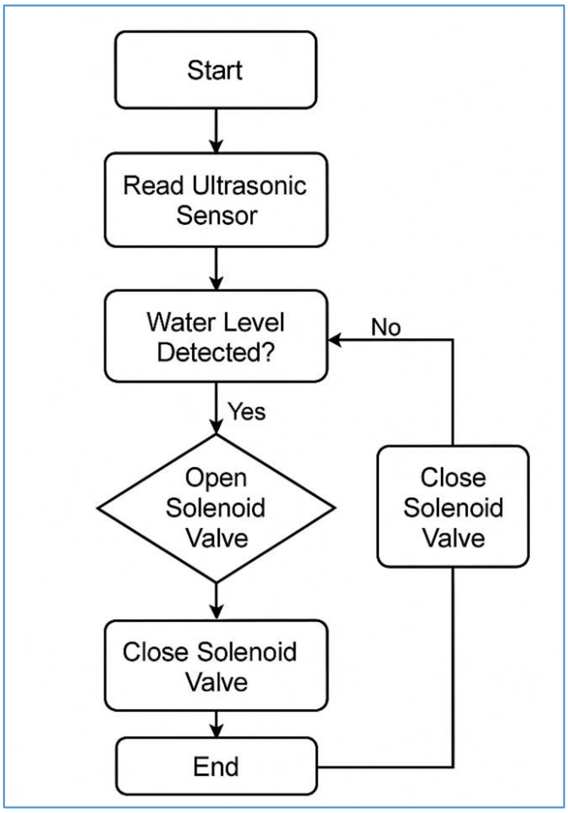

Figure 2. Aquaclove system flow diagram

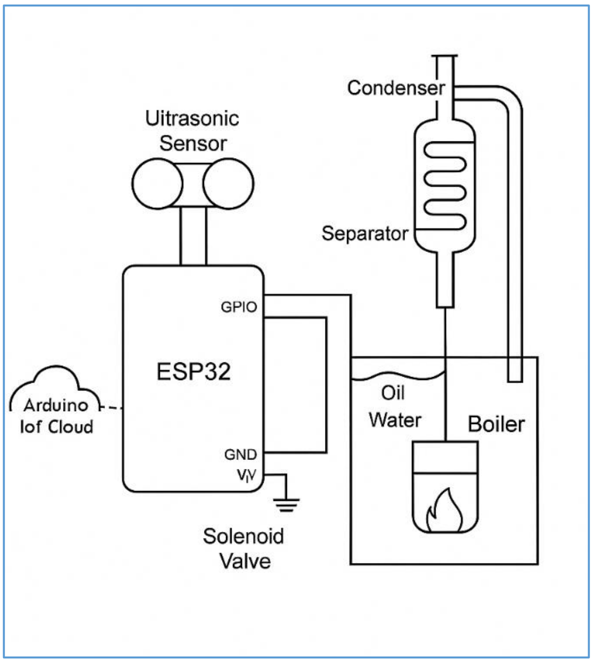

Figure 3. Physical design of the aquaclove system

Figures 2 and 3 illustrate the operational workflow and physical configuration of the AquaClove system, respectively. Figure 2 presents the control logic of the system, highlighting the sequential steps from sensor input to solenoid valve actuation. Figure 3 depicts the physical architecture, showing the integration of the ESP32 microcontroller, ultrasonic sensor, solenoid valve, and distillation components, including the separator and condenser. These diagrams are essential to understanding the automation and IoT-based control mechanisms implemented in the proposed system.

The first stage involved evaluating sensor accuracy using an ultrasonic sensor. Multiple fluid levels were simulated using controlled volumes of clove-water mixture. The sensor output was compared to manual measurements using a graduated cylinder. As shown in Table 1, the ultrasonic sensor consistently provided readings with a deviation of less than ±2 mm, indicating high precision in real-time fluid detection. This finding aligns with the studies by Yu et al. [13] and Ni et al. [15], who reported similar levels of accuracy in ultrasonic-based liquid detection systems.

Table 1. Sensor accuracy measurement

Trial	Actual Level (cm)	Sensor Reading (cm)	Deviation (cm)
1	12.0	11.8	0.2
2	15.0	14.9	0.1
3	18.5	18.7	-0.2

The second stage focused on solenoid valve responsiveness. The valve was controlled via ESP32 microcontroller based on predefined thresholds from sensor input. As visualized in Figure 2, the system achieved an average response time of 0.8 seconds from command issuance to valve actuation. This performance is considered highly efficient compared to conventional systems that require manual timing or delay-based controls. The result supports prior findings by Tang et al. [24], emphasizing the viability of using solenoid valves in automated fluid systems.

The responsiveness of the solenoid valve was evaluated based on its actuation time upon receiving control signals from the ESP32 microcontroller. As shown in Figure 4, the valve achieved a full open position within approximately 1.5 seconds, following a smooth S-curve trajectory. This behavior

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indicates a stable and predictable dynamic response, which is critical for precise fluid control in automated distillation systems.

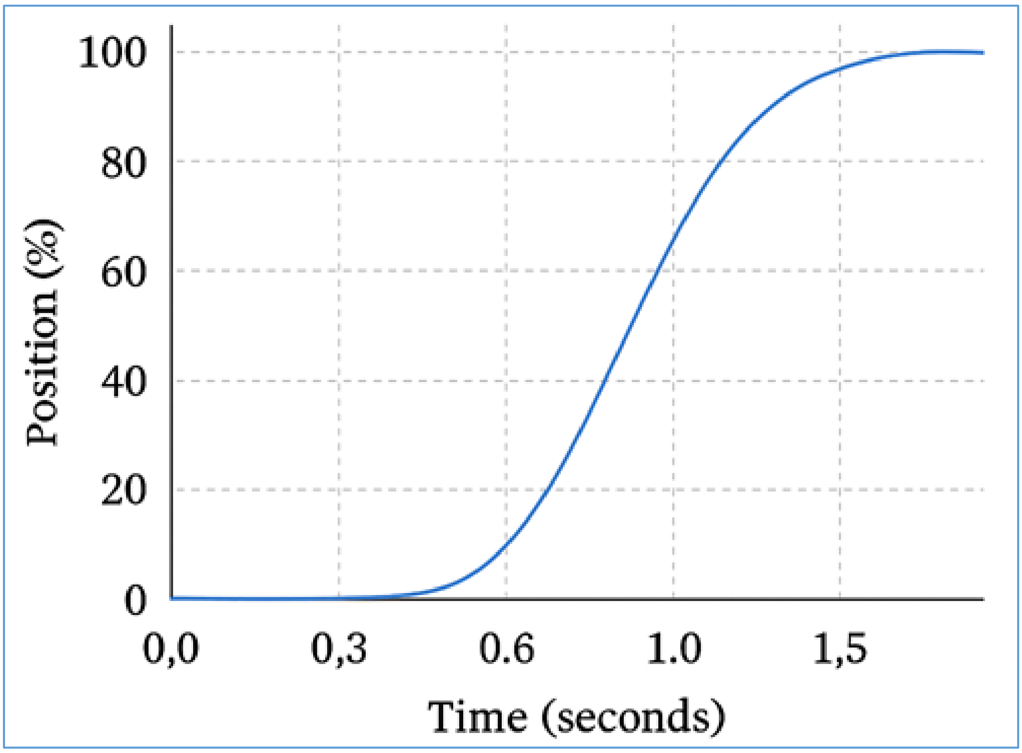

Figure 4. Valve actuation response curve

The third component evaluated was the IoT integration, specifically data transmission to Arduino IoT Cloud. The system recorded and transmitted sensor values and valve states every 5 seconds with less than 1% packet loss, even under varied network conditions. This finding underscores the robustness of the ESP32-IoT platform combination, as also highlighted in the work of Talbi et al. [18] and Nur-A-Alam et al. [20]. Figure 5 displays a screenshot of the cloud dashboard showing real-time liquid levels and valve status during operation.

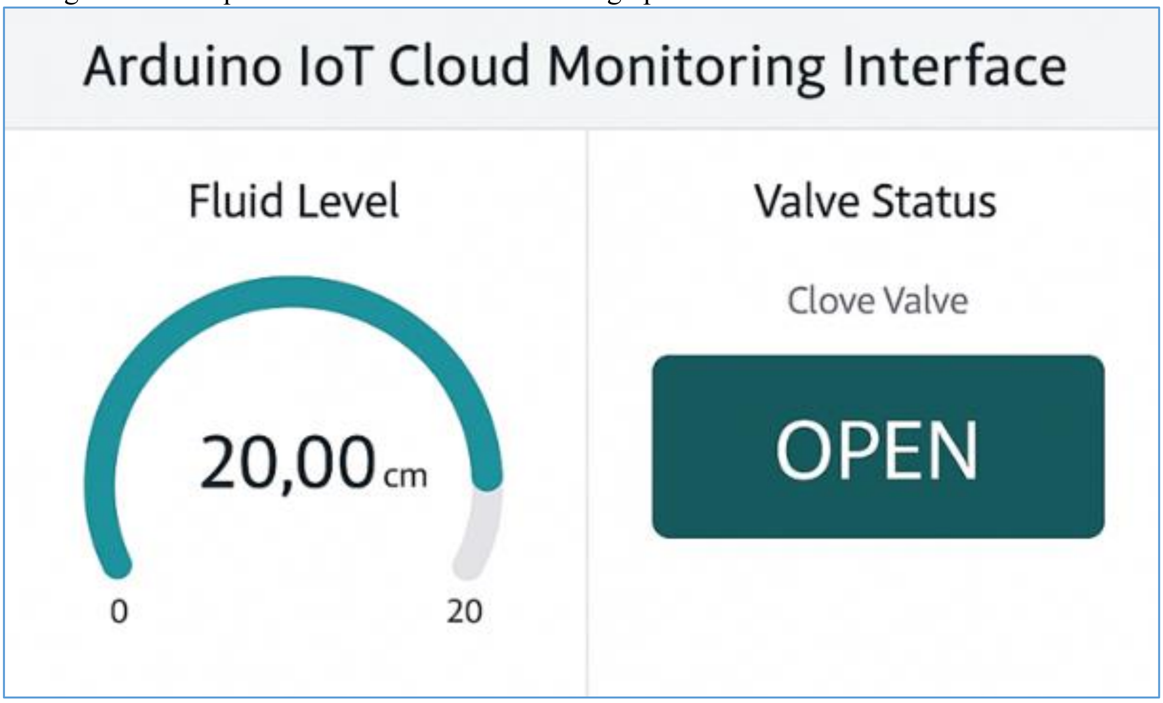

Figure 5. Arduino IoT cloud monitoring interface

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A simulated representation of the real-time monitoring dashboard, developed using Arduino IoT Cloud, displays fluid level readings and solenoid valve status for remote tracking purposes.

Finally, the overall efficiency improvement was evaluated by comparing manual and automated distillation processes. With AquaClove, total distillation time was reduced by 32%, and labor input was cut by 55%, as illustrated in Table 2. These improvements are significant, especially for small-scale producers seeking to scale operations without proportional labor increase.

Table 2. Comparison of manual and automated distillation

Parameter	Manual Process	AquaClove System	Improvement (%)
Average Distillation Time	4.2 hours	2.9 hours	31.0
Number of Labor Personnel	3 persons	1 person	66.7
Oil Loss (per 10 L batch)	0.6 L	0.2 L	66.7

These results demonstrate that AquaClove not only automates the process but also ensures measurable improvements in productivity and consistency. Compared to previous systems that either focused on single-function sensing or generic automation, AquaClove uniquely combines real-time sensing, automated fluid actuation, and cloud-based monitoring into a compact, scalable solution tailored to clove oil production.

Moreover, its modular design and use of low-cost open-source components (ESP32, Arduino IDE, and ultrasonic sensors) offer a highly replicable model, particularly for community-level or rural distillation units. This differentiates AquaClove from prior research and demonstrates the novelty and real-world applicability of the system.

5. Conclusion

This study has successfully developed AquaClove, an automated clove essential oil distillation system that integrates ultrasonic sensing, solenoid valve actuation, and real-time IoT-based monitoring via the ESP32 microcontroller. The system addresses key challenges in traditional distillation, particularly in the oil-water separation stage, by reducing manual intervention, improving precision, and increasing overall process efficiency. Compared to conventional methods, AquaClove reduced distillation time, minimized oil loss, and lowered labor requirements, making it a scalable and cost-effective solution for small- to medium-scale operations.

However, several limitations were identified during the study. Sensor performance may degrade over time in humid environments, requiring recalibration. Internet connectivity remains a critical factor for stable cloud-based monitoring, which could limit deployment in rural areas. Additionally, while component costs are relatively low, initial setup expenses may still be a concern for micro-scale producers. Future work should explore improving hardware durability, reducing cloud dependency through edge computing, and expanding system adaptability for various essential oil types.

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