Design and Development of Cost Efficient Sanitization Device for Beverage Vendors

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Abstract: *Street beverage vendors face significant challenges in maintaining utensil hygiene due to resource constraints, heavily relying on manual washing methods. This practice often leads to suboptimal sanitization and increased cross-contamination risks. While commercial automated dishwashing solutions exist, they are cost-prohibitive, oversized, and laden with unnecessary features for small-scale operations. This paper presents the design, development, and validation of a highly compact, cost-efficient, and automated glass sanitization system tailored specifically for street vendors. The proposed system employs an Internet of Things-enabled microcontroller to orchestrate a multi-stage cleaning cycle. It utilizes a high-pressure diaphragm pump, strategically distributed conical spray nozzles for balanced mechanical glass stabilization, and an inline pulse-width modulated solenoid valve for precise soap dosing without relying on dedicated dosing pumps. A unified low-voltage electrical architecture, managed via an optically isolated relay module and step-down converter, ensures safe operation in wet environments. Furthermore, hardware-level logic interlocks provide a touchless, fail-safe user experience, while an optional ultraviolet sanitization phase serves as an additional biological kill-step. Designed with a modular, right-to-repair philosophy using commercial off-the-shelf components, this machine provides an affordable alternative to traditional commercial dishwashers. By deploying this system, vendors can elevate their hygiene standards, establish a visible unique selling proposition for health-conscious consumers, and optimize resource consumption.*

Keywords: Automated Glasswasher, Street Vendor Hygiene, Internet of Things, Pulse-Width Modulation, Solenoid Valve Control, Low-Cost Appliance,

I. INTRODUCTION

The informal food and beverage sector, primarily driven by street vendors, plays a crucial economic role in developing nations by providing accessible and affordable sustenance. However, this sector faces persistent challenges regarding food safety and utensil hygiene. Due to severe constraints in space, capital, and continuous water supply, the majority of street beverage vendors rely entirely on manual washing methods. Studies have shown that traditional practices—such as repeatedly dunking glasses in a single communal bucket of increasingly contaminated water or using unreplaced wash-sponges—lead to significant microbial cross-contamination [1]. Furthermore, demographic investigations reveal a general lack of formal food safety training among vendors, exacerbating the risks of foodborne illnesses associated with improperly sanitized food-contact surfaces [2], [3].

Concurrently, there is a growing demographic of health-conscious consumers, particularly among older populations, who are willing to pay a premium for hygienically prepared beverages. This shift in consumer perception presents a unique opportunity: visible hygiene practices can serve as a highly effective Unique Selling Proposition (USP) for vendors. Despite this demand, upgrading to automated sanitization remains economically unfeasible for micro-businesses. Standard commercial dishwashers and glasswashers currently available in the market are prohibitively expensive (often exceeding ₹25,000 INR), possess a large physical footprint, and feature bloated wash cycles with high energy demands (such as integrated water heaters) that are unnecessary for cleaning simple liquid beverage residues.

ISSN: 2581-9429
Volume 6, Issue 19, April 2026
Impact Factor: 8.2

To bridge this critical market gap, this research proposes the design and development of a scaled-down, highly dedicated, and cost-efficient automated glass sanitization system. Engineered with a strict budget constraint (prototype cost of approximately ₹6,000 INR), the system strips away the superfluous features of traditional dishwashers to focus strictly on the physical and chemical requirements of washing beverage glasses. By leveraging low-cost Internet of Things (IoT) frameworks [4]—specifically the ESP32 microcontroller—the system achieves precise, automated control over high-pressure fluid dynamics and chemical dosing [5].

The proposed architecture features a compact, microwave-inspired form factor (50 × 23 × 23 cm) tailored for small vendor carts. It utilizes a 12V 220 PSI direct-current diaphragm pump, strategically distributed stainless-steel conical nozzles, and a pulse-width modulated (PWM) solenoid valve mechanism for inline soap dosing. A primary design objective is to maintain a modular, "Right-to-Repair" philosophy using commercial off-the-shelf (COTS) components, ensuring vendors can independently maintain the machine without expensive service contracts.

II. RELATED WORK AND PROBLEM FORMULATION

A. Traditional Washing Methods

The operational constraints of street food and beverage vending often force reliance on primitive utensil sanitization techniques. Extensive field studies demonstrate that a vast majority of vendors utilize a single, static basin of water to repeatedly rinse glasses and plates throughout their operational hours [1]. This static water approach, coupled with the infrequent replacement of wash-sponges, creates a high-risk environment for microbial proliferation and cross-contamination. Research evaluating the microbial quality of such vending sites has documented severe bacterial loads on food-contact surfaces, directly correlating poor utensil hygiene with localized outbreaks of foodborne illnesses [3]. Furthermore, investigations into vendor demographics reveal a systemic lack of formal food safety education [2]. Consequently, vendors prioritize the speed and resource efficiency (minimal water and energy usage) of manual washing over stringent sanitization protocols, highlighting a critical need for an automated solution that requires zero active thought or procedural training from the user.

B. Microcontroller-Based Systems

In the realm of domestic and commercial appliance automation, the integration of low-cost embedded systems has drastically reduced the barrier to entry for smart device development. Literature on energy conservation and appliance automation frequently highlights microcontrollers, such as the ESP32, as highly effective orchestrators for load switching and resource management [6]. Recent studies proposing minimal-water-usage dishwashers have successfully utilized Internet of Things (IoT) frameworks to control fluid dynamics and cycle timing without the need for expensive, proprietary control boards [4]. Additionally, the robust capability of the ESP32 to interface with cloud services and local web networks, while safely switching high-current inductive loads (such as pumps and solenoid valves) via optically isolated relays, has been well documented in smart-home automation research [5]. These studies validate that commercial-grade appliance logic can be achieved using affordable, commercially available microcontrollers.

C. Research Gap and Contribution

Despite the critical hygiene deficits in the street vending sector and the availability of low-cost microcontrollers, a significant research and market gap exists. Current commercial dishwashers and dedicated glasswashers are engineered for large-scale restaurants. They are prohibitively expensive (averaging ₹25,000 INR or more), demand extensive physical space, and rely on high-power heating elements and continuous pressurized plumbing. These systems are fundamentally incompatible with the economic and infrastructural realities of a street vendor's cart.

This research bridges this gap by formulating a highly targeted, scaled-down automated glasswasher dedicated exclusively to beverage residues. The primary contributions of this work are:

[1] Cost-Efficient Architecture: Developing a functional prototype for approximately ₹6,000 INR, drastically reducing the payback period for micro-businesses.

DOI: 10.48175/IJARSCT-34487

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 19, April 2026
Impact Factor: 8.2

[2] Resource Optimization: Eliminating unnecessary features, such as water heaters and complex rotating spray arms, in favor of an ambient-water, high-pressure stationary manifold system.

[3] Innovative Dosing Control: Implementing a pulse-width modulated (PWM) solenoid valve at a T-junction for inline soap injection, completely bypassing the need for expensive secondary dosing pumps.

[4] Right-to-Repair Design: Constructing the entire chassis and hydraulic system using modular, easily detachable Commercial Off-The-Shelf (COTS) components, empowering vendors with independent maintenance capabilities.

III. SYSTEM ARCHITECTURE AND HARDWARE DESIGN

A. Design Goals

The primary objective of the proposed system architecture is to deliver a highly efficient, automated sanitization process within strict financial and spatial constraints. The design goals emphasize a compact physical footprint (50 × 23 × 23 cm) suitable for vendor carts, a unified low-voltage power distribution for safety in wet environments, and the complete elimination of unnecessary moving parts (such as rotating spray arms) to minimize maintenance. Furthermore, the architecture adheres to a "Right-to-Repair" philosophy, utilizing standard Commercial Off-The-Shelf (COTS) components to ensure the system is entirely modular and independently maintainable by the end-user.

B. Control Unit: ESP32 Microcontroller

To achieve smart appliance capabilities without the cost of proprietary control boards, the ESP32 microcontroller serves as the central processing unit of the machine. The ESP32 was selected for its low cost, extensive General-Purpose Input/Output (GPIO) availability, and embedded Wi-Fi module. Operating in Access Point (AP) mode, the microcontroller hosts a localized, user-friendly web interface. This allows the vendor to wirelessly customize cycle parameters—such as wash duration and soap dosing intervals—directly from a smartphone without requiring an external internet connection or router.

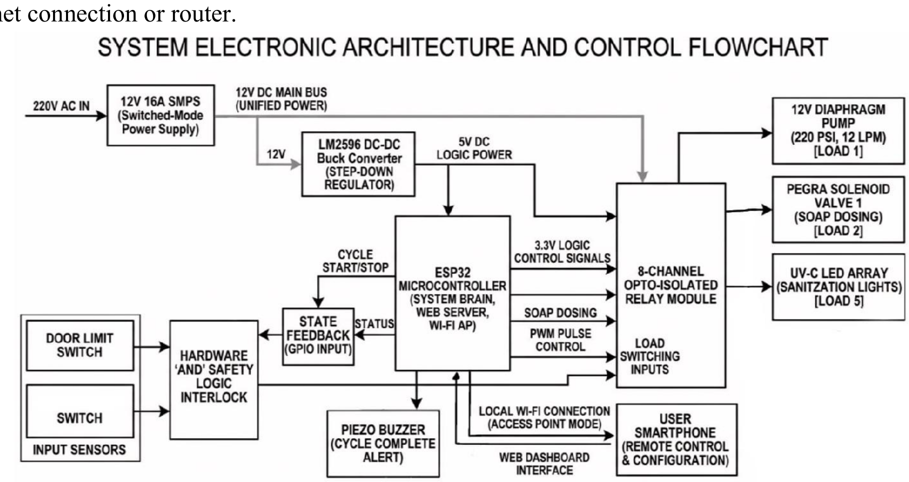

Fig.1: Detailed Electronics Control and Power Distribution Flowchart for the IoT- Enabled Smart Glasswasher

C. Water Nozzle Structure

Traditional dishwashers rely on rotating spray arms, which introduce mechanical complexity and require significant water volume to maintain momentum. To resolve this, the proposed architecture employs a stationary, high-pressure manifold system. The wash cabinet is equipped with 12 stainless steel nozzles, configured with 6 positioned above the glasses and 6 below. These nozzles are engineered to produce a conical mist spray. By running the upper and lower manifolds simultaneously, the system creates a dispersed, omnidirectional pressure equilibrium. This strategically pins

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 19, April 2026
Impact Factor: 8.2

the upside-down glasses onto the tray, completely neutralizing the upward kinetic force of the high-pressure water and preventing the glasses from rattling or shattering without the need for mechanical clamps.

D. Relay and Pump Control

Fluid propulsion is achieved using a 12V direct-current (DC) diaphragm pump featuring a 220 PSI cutoff pressure and a maximum flow rate of approximately 12 Liters Per Minute (LPM). Fluid routing is managed by three 12V PEGRA solenoid valves (1/2" BSPM, 30 LPM capacity), dictating flow to the soap intake, upper manifold, and lower manifold. Because the pump and solenoid coils are heavy inductive loads capable of generating severe flyback voltage spikes, an 8-channel 5V relay module (utilizing Tongling JQC-3FF-S-Z relays) is employed for switching. Crucially, this relay board features EL817 optocouplers, which physically isolate the sensitive 3.3V logic signals of the ESP32 from the high-power 12V mechanical loads, ensuring system stability and preventing microcontroller resets during operation.

E. Power Supply and Distribution

To maximize electrical safety and simplify wiring, the system operates on a unified 12V architecture driven by a single 12V 16A Switched-Mode Power Supply (SMPS). This high-amperage unit provides sufficient overhead to handle the simultaneous inrush currents of the diaphragm pump and the solenoid valves. Power distribution is divided into two discrete paths. The high-power path directly supplies the relay module to drive the mechanical components and optional UV-C LEDs. For the logic control path, an LM2596 DC-DC buck converter is utilized. This high-efficiency switching regulator steps the 12V source down to a stable 5V to power the ESP32 and the relay logic circuitry, drastically reducing heat dissipation compared to standard linear voltage regulators.

F. Emergency Safety System

Given the use of high-pressure fluid and optional ultraviolet (UV-C) sanitization, user safety is enforced at the hardware level to eliminate software failure risks. The safety architecture utilizes physical limit switches positioned on both the sliding glass tray and the main exterior door. These switches are wired in a hardware 'AND' logic configuration. The microcontroller will only initiate a wash cycle if both conditions are met: the tray is fully inserted AND the door is securely closed. If the vendor accidentally opens the door mid-cycle, the limit switch immediately breaks the circuit, instantaneously cutting power to the pump and UV lights. This creates a fool-proof, zero-interaction safety barrier suitable for fast-paced commercial environments.

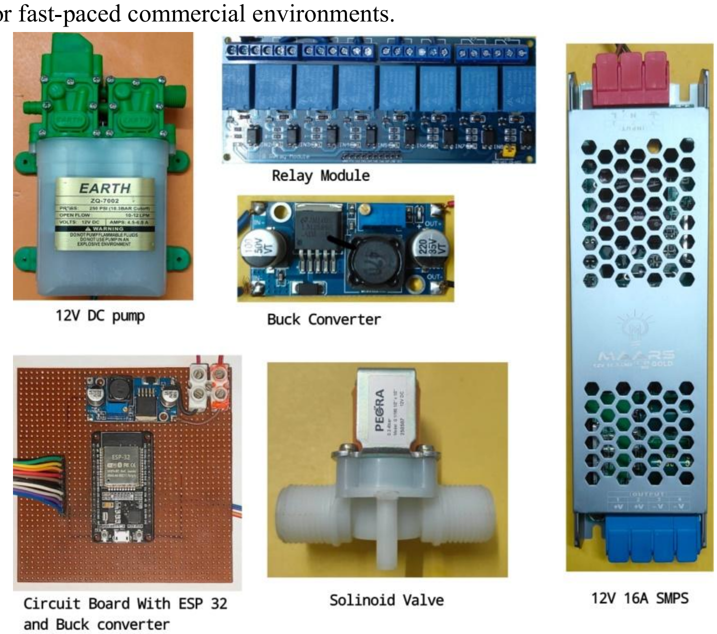

Fig.2: Electronic Components

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
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IV. MODULAR CABINET ARCHITECTURE

The physical structure of the automated glasswasher is designed around a strict "Right-to-Repair" and commercial off-the-shelf (COTS) philosophy. The exterior chassis, measuring 50 × 23 × 23 cm, is constructed entirely from Aluminum Composite Panels (ACP). ACP was selected for its high strength-to-weight ratio, professional aesthetic, and absolute resistance to both rust and ultraviolet (UV) degradation. To ensure the machine remains serviceable by the vendor without specialized tools, the architecture is highly modular, with every structural and plumbing component designed to be easily detachable.

Fig. 3: Cabinet CAD Model

A. Wash Cabinet

The wash cabinet constitutes the primary mechanical chamber where high-pressure fluid dynamics and chemical sanitization occur. The interior floor is intentionally sloped toward a central outlet, facilitating a zero-energy, gravity-fed drainage system that rapidly evacuates wastewater to an external receptacle.

1**) Nozzles:** The primary cleaning mechanism consists of twelve threaded, stainless-steel spray nozzles. Configured with six positioned on the upper interior panel and six on the lower panel, these nozzles generate an overlapping conical mist. The threaded design is crucial for maintenance; because vendors may draw water from open buckets containing fine silt, the nozzles can be easily unscrewed, cleaned, and replaced by the user if clogging occurs.

2) **Tray:** To minimize loading time and improve vendor workflow, the system utilizes a removable "magazine-style" tray system. The tray is fabricated from a durable stainless-steel mesh arranged in a 3×2 grid, accommodating six standard beverage glasses inverted simultaneously. The open mesh design offers minimal fluid resistance, allowing the high-pressure spray from the lower manifold to directly penetrate the interior of the glasses while facilitating rapid passive drip-drying post-cycle.

3) Limit Switches: As part of the primary hardware interlock system, a mechanical limit switch is mounted at the terminus of the internal tray guide rail. This sensor provides physical verification that the stainless-steel mesh tray is fully inserted and correctly seated within the wash zone before the microcontroller permits the activation of the high-pressure pump.

4) UV LED Strip: To provide a secondary, biological kill-step, 12V UV-C LED strips are mounted within the vertical corners of the wash cabinet. Standard soda-lime beverage glass inherently blocks UV-C wavelengths; therefore, these lights are strategically positioned to sanitize the exterior surfaces of the glasses where cross-contamination from the vendor's hands is most likely to occur. Furthermore, the programmed UV-C phase acts as an operational buffer, allowing residual water to passively drip off the glasses before the cycle completion buzzer sounds.

5) Door and Shutter: Containing the aggressive fluid dynamics of the 220 PSI pump within a compact enclosure presents a significant sealing challenge. Rather than relying on complex mechanical latches that degrade over time, the front-opening door is secured using high-strength neodymium magnets. This is paired with a continuous, commercial-

DOI: 10.48175/IJARSCT-34487

grade silicone gasket lining the perimeter of the opening. This magnetic sealing mechanism ensures zero water leakage during the pressurized wash cycle while maintaining a seamless, zero-effort ergonomic experience for the user.

B. Electronic Cabinet

To ensure absolute electrical safety and prevent moisture ingress from the high-pressure wash zone, all computational and power distribution components are housed in an isolated, dry electronic cabinet located adjacent to the wash chamber. This modular separation allows for safe and immediate access to the circuitry for diagnostics and repairs

1) Power Supply: The foundational energy source for the entire system is a 12V, 16A Switched-Mode Power Supply (SMPS). By utilizing a unified 12V architecture, the system safely eliminates the need to route hazardous 220V AC mains power throughout the chassis. The 16A current rating provides substantial electrical headroom to comfortably manage the high inrush currents generated by the simultaneous activation of the diaphragm pump and multiple solenoid coils.

2) Zero PCB and Embedded Logic: The central processing hardware is assembled on a standard Zero PCB (perfboard) to maintain strict prototype cost-efficiency. This board houses three critical sub-components: the ESP32 microcontroller, an LM2596 DC-DC buck converter, and a piezoelectric buzzer. Because the ESP32 operates on sensitive 3.3V logic, exposing it directly to the 12V main line would cause catastrophic thermal failure. The LM2596 buck converter is utilized to efficiently step down the 12V SMPS output to a highly stable 5V, minimizing heat dissipation. The ESP32 utilizes this regulated power to execute the wash cycle logic and broadcast its Wi-Fi Access Point. Upon the successful completion of a sanitization cycle, the ESP32 triggers the onboard buzzer, providing distinct auditory feedback to the vendor so they can retrieve the clean glasses.

3) Relay Module: Load switching is managed by an 8-channel, 5V relay board equipped with Tongling (JQC-3FF-S-Z) mechanical relays. A critical engineering challenge in fluid automation is the flyback voltage generated when inductive loads (like motors and magnetic coils) are deactivated, which can easily crash a microcontroller. To prevent this, the selected relay module features EL817 optocouplers. These optocouplers physically isolate the ESP32's low-voltage logic signals from the 12V high-current switching paths using light, ensuring the microcontroller remains entirely unaffected by inductive voltage spikes.

4) Solenoid Valves: Fluid routing is electronically controlled via three discrete 12V PEGRA solenoid valves. Rated for a maximum flow of 30 Liters Per Minute (LPM) and an operating pressure of 0.02 to 0.8 MPa, these valves perfectly complement the 220 PSI cutoff pressure of the diaphragm pump. Two of these normally-closed valves are dedicated to independently controlling the water flow to the upper and lower nozzle manifolds, allowing for future cycle variations or targeted pressure adjustments.

5) Soap System: The third solenoid valve dictates the automated chemical dosing mechanism. Rather than utilizing an expensive, dedicated peristaltic dosing pump, the system achieves inline soap injection using a simple T-connector on the pump's inlet line. One branch of the T-connector is attached to the ambient water reservoir, while the other is connected to a low-viscosity liquid soap reservoir via the third solenoid valve. When soap is required, the ESP32 applies Pulse-Width Modulation (PWM), rapidly toggling the valve open and closed for just 1 to 2 seconds. This precise, software-driven mechanical pulsing draws a highly controlled, minimal volume of soap into the main water line, preventing excessive foaming within the wash cabinet while maximizing resource efficiency.

IJARSCT
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ISSN: 2581-9429
Volume 6, Issue 19, April 2026
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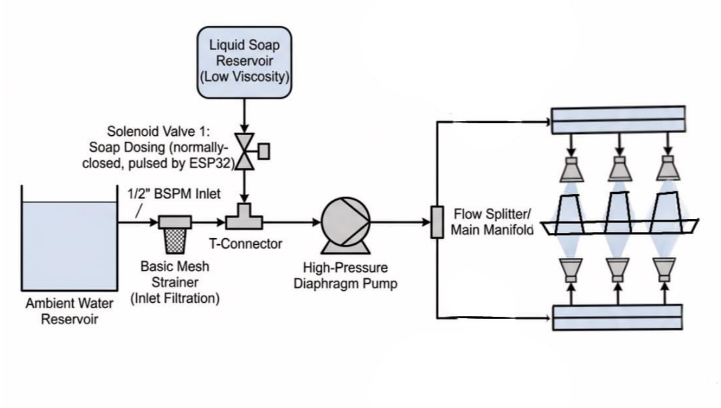

Fig. 4 : Fluid Dynamics and Sanitization Schematic Diagram

V. AUTONOMOUS CONTROL LOGIC

A. Control Logic

The operational sequence of the automated glasswasher is governed by a finite state machine programmed into the ESP32 microcontroller. To minimize the cognitive load on the vendor, the system operates entirely autonomously once the physical safety conditions are met. The standard execution sequence is divided into four primary states: Pre-Wash, Chemical Dosing, Final Rinse, and Ultraviolet Sanitization.

Upon activation, the system initiates the Pre-Wash state by engaging the main diaphragm pump and simultaneously opening both the upper and lower manifold solenoid valves, utilizing ambient water to mechanically blast away loose beverage residues. Following this, the system transitions into the Chemical Dosing state. The microcontroller applies a rapid Pulse-Width Modulation (PWM) signal to the soap intake solenoid valve, introducing a precise, highly concentrated burst of liquid soap into the fluid stream. The system then enters the Final Rinse state, closing the soap valve and resuming a pure water spray to clear the suds and remaining contaminants. Finally, the pump is deactivated, and the system enters the Ultraviolet Sanitization state. The UV-C LEDs are engaged to sanitize the exterior glass surfaces while providing a passive buffer period for excess water to drip off the internal mesh tray. Upon completion of this final state, the ESP32 triggers the piezoelectric buzzer, signaling to the user that the glasses are clean and ready for retrieval.

B. Safety System

Given the integration of high-pressure fluid, electrical components, and UV-C radiation, robust user safety mechanisms are paramount. Rather than relying solely on software-based interrupts—which are susceptible to failure if the microcontroller freezes or crashes—the system employs a fail-safe, hardware-level interlocking architecture.

Two physical limit switches are utilized: one positioned on the internal tray guide rail and another on the primary magnetic door. These switches are wired in a strict hardware 'AND' configuration. The electrical circuit supplying power to the main pump relay and the UV-C lighting relay is physically incomplete unless both switches are simultaneously depressed. Consequently, the system will auto-activate only when the vendor fully inserts the loaded tray and securely closes the door. This zero-button activation design is highly ergonomic for fast-paced street vending environments. Furthermore, if the door is accidentally or intentionally opened midway through an active cycle, the limit switch circuit is instantly broken. This immediately halts the high-pressure spray and extinguishes the UV-C radiation, neutralizing any risk of physical injury or ocular exposure before the software even registers the event.

DOI: 10.48175/IJARSCT-34487

VI. WEB PAGE DASHBOARD

A. Customizable Options

To accommodate varying levels of residue and different types of liquid soaps, the automated glasswasher features a highly adaptable software architecture. The ESP32 microcontroller is configured to broadcast its own localized Wi-Fi hotspot, operating in Access Point (AP) mode. By connecting a standard smartphone or computer to this local network, the vendor can access a dedicated, user-friendly HTML web interface hosted directly on the microcontroller.

This dashboard serves exclusively as an administrative configuration tool. It allows the user to fine-tune the temporal parameters of the finite state machine. Customizable options include adjusting the duration of the Pre-Wash and Final Rinse phases, modifying the length of the pulse-width modulated (PWM) Chemical Dosing interval to control soap volume, and extending or reducing the Ultraviolet (UV-C) sanitization buffer time. Additionally, the dashboard includes a software toggle to completely disable the soap dosing phase, which is particularly useful if the vendor runs out of detergent or is washing lightly soiled glasses that only require a high-pressure water rinse.

Crucially, the system is designed for asynchronous, "headless" operation. A connected mobile device is not required to initiate or operate the daily wash cycles. Once the vendor submits their customized parameters via the web dashboard, the data is written to the non-volatile flash memory of the ESP32. The system will continuously utilize these saved parameters for all subsequent wash cycles, seamlessly retaining the configuration even after the machine is completely powered off and unplugged at the end of the day. This design ensures that the vendor's daily workflow remains frictionless and entirely hands-free, requiring digital intervention only when a change in cleaning parameters is strictly necessary.

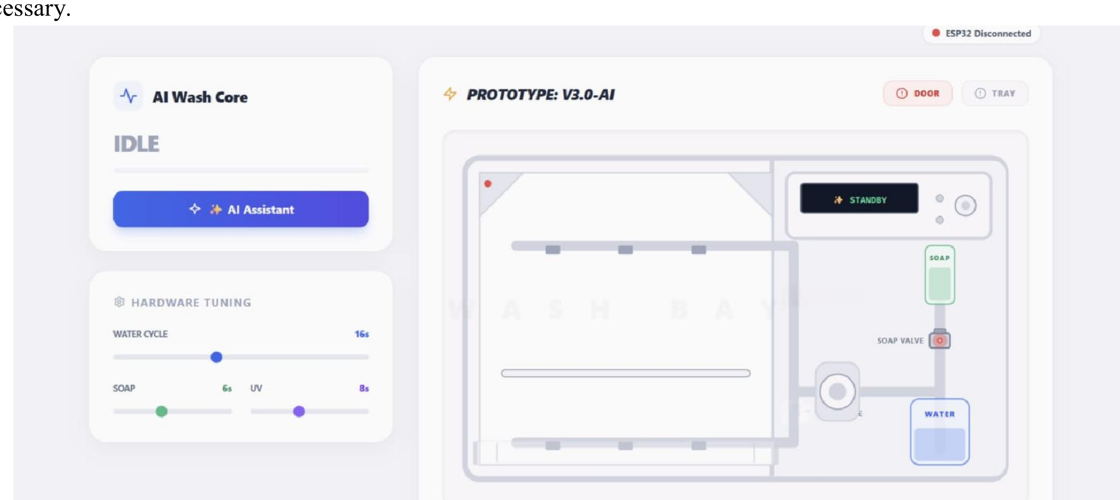

Fig.5 : Interactive Webpage Dashboard for Glass Wash Cycle Customization

VII. EXPERIMENTAL RESULTS

To validate the operational efficiency, resource consumption, and economic viability of the automated glasswasher, empirical testing was conducted. A standard test cycle was defined as 40 seconds (7s Pre-Wash, 3s Chemical Dosing, 10s Final Rinse, 20s UV/Drip Dry), suitable for low-viscosity beverage residues. Data for each parameter was collected across three distinct trials and averaged to ensure statistical reliability.

A. Fluid Dynamics and Water Consumption

System flow rate and total water consumption were measured by routing the gravity drain output into a graduated collection vessel. To measure nozzle flow distribution and pressure drop, flexible tubing was fitted to a 3-nozzle series branch, draining into separate 500 mL containers to calculate individual flow rates.

TABLE II: System Water Consumption (40-Second Cycle)

Parameter	Trial 1	Trial 2	Trial 3	Average
Total Volume Used (mL)	1375	1385	1378	1379.3
Active Flow Rate (LPM)	4.12	4.15	4.13	4.13

TABLE III: Flow Distribution Across 3-Nozzle Series Manifold

Nozzle Position	Trial 1 (s)	Trial 2 (s)	Trial 3 (s)	Avg Fill Time (s)	Flow Rate (mL/s)
Nozzle 1 (Inlet)	84.5	85.2	85.3	85.0	5.88
Nozzle 2 (Middle)	86.8	87.1	87.1	87.0	5.75
Nozzle 3 (Terminal)	88.5	89.2	89.3	89.0	5.62

Observation: The system utilizes approximately 1.38 Liters per cycle. The flow drop across the series manifold is highly marginal (0.26 mL/s variance), confirming uniform pressure distribution without the need for complex compensatory valves.

B. Electrical and Energy Consumption

Power metrics were captured using a digital inline DC wattmeter and a cumulative energy meter placed between the 12V SMPS and the relay distribution board. Peak load occurs during the Chemical Dosing phase when the pump, dual main solenoids, and the PWM soap solenoid are active simultaneously.

TABLE IV: Electrical Power and Energy Dra

Parameter	Trial 1	Trial 2	Trial 3	Average
Active Peak Power (W)	93.1	94.2	93.5	**93.6**
Cycle Energy (Wh)	0.552	0.558	0.558	**0.556**

Observation: The peak power draw of 93.6 W remains well below the 192 W capacity of the 16A SMPS, ensuring safe thermal overhead. Energy consumption per cycle is remarkably low at 0.556 Wh (0.000556 kWh).

C. Throughput Capacity and Economic Feasibility

Operational throughput was calculated assuming a 5-second reload interval to swap the magnetic mesh trays between 40-second cycles. Economic feasibility was determined using standard commercial tariffs in India (Electricity @ ₹8/kWh, Bulk Water @ ₹100/1000L, Liquid Soap @ ₹150/1000mL, assuming 5 mL soap per cycle).

TABLE V: Operational Throughput and Cost Analysis

Metric	Calculated Value
Batch Time (Cycle + Reload)	45 Seconds
Hourly Throughput Capacity	80 Batches (480 Glasses)
Electricity Cost / Cycle	₹ 0.0044
Water Cost / Cycle	₹ 0.1380
Soap Cost / Cycle	₹ 0.7500
Total Cost / Cycle (6 Glasses)	₹ 0.8924
Cost Per Glass	₹ 0.148 (~0.15 INR)

Observation: The system yields a high operational throughput of 480 glasses per hour. At an operational cost of approximately 15 Paisa per glass, the automated system achieves financial viability for micro-businesses while eliminating manual labor.

ISSN: 2581-9429
Volume 6, Issue 19, April 2026
Impact Factor: 8.2

VIII. CONCLUSION AND FUTURE WORK

A. Conclusion

The development of this automated glass sanitization system successfully addresses a critical hygienic and economic gap in the informal food and beverage sector. By prioritizing essential cleaning mechanics over superfluous features, the project achieved its primary objectives:

I. **Economic Viability:** The prototype was successfully constructed within the ₹6,000 INR budget using modular Commercial Off-The-Shelf (COTS) components, yielding an operational cost of approximately 15 Paisa per glass.

II. **Resource Efficiency:** The use of an ESP32 microcontroller, inline PWM soap dosing, and a stationary high-pressure manifold eliminated the need for continuous plumbing, dedicated dosing pumps, and heavy water consumption, utilizing only ~1.38 liters per cycle.

III. **Operational Excellence:** With a hardware-locked safety system and a robust 12V DC architecture, the machine safely achieves a high throughput of up to 480 glasses per hour, transforming a manual, high-risk chore into a passive, "zero-touch" automated process.

B. Future Work

While the current prototype effectively standardizes utensil hygiene, future iterations of the system will focus on artificial intelligence, enhanced user accessibility, and ergonomic hardware refinements:

1. **AI-Driven Cycle Optimization:** Future software architecture will integrate an Artificial Intelligence (API) endpoint directly into the ESP32 web server. Rather than manually adjusting time parameters, the user will simply input the type of beverage residue (e.g., "thick milkshake" or "black tea"). The AI will evaluate the viscosity and automatically calculate the optimal pre-wash, soap PWM, and rinse durations to maximize resource conservation.
2. **Messaging App Integration for Accessibility:** To accommodate vendors with varying levels of digital literacy, the web interface will be bridged with popular messaging platforms like WhatsApp. Users will be able to simply text the beverage type to a dedicated bot, which will seamlessly interface with the AI API to configure the machine, entirely bypassing the need to navigate a traditional web browser.
3. **Ergonomic Chassis Redesign:** The physical exterior of the cabinet will be refined to replace the current sharp, angled dimensions with a curved, edge-free geometric profile. This will enhance the overall ergonomics, aesthetic appeal, and physical safety of the unit in cramped, fast-paced street vending environments.
4. **Automated Shutter Release:** To further streamline the vendor's workflow and aid in passive drying, a 12V solenoid latch paired with a mechanical spring tensioner will be added to the door assembly. Upon the completion of the UV-C sanitization phase, the microcontroller will trigger the latch, autonomously popping the door open to provide immediate visual feedback that the cycle has concluded.

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ISSN: 2581-9429
Volume 6, Issue 19, April 2026
Impact Factor: 8.2

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DOI: 10.48175/IJARSCT-34487