

# HygieHelm: An IoT-Enabled Automated Helmet Sanitization Kiosk using ESP32 Microcontroller

Tejas H. R., Dhruv Kumar and Lohith R. D.

School of Engineering, Dayananda Sagar University, Bengaluru, Karnataka, India

**Abstract** - Motorcycle helmet liners take a beating from daily commuting - soaked in sweat, coated in sebum, dusted with road grime. Most riders never clean them, quietly breeding scalp pathogens. To tackle this, we built HygieHelm, a self-service sanitization kiosk costing under USD 52, completing a full 6-minute cycle with no user disassembly required.

The kiosk runs on an ESP32 microcontroller executing a non-blocking Finite State Machine (FSM), with Firebase handling cloud telemetry. Each cycle walks through four stages: a 12V vacuum motor pulls out loose debris, a 1.7 MHz ultrasonic transducer mists the interior to rehydrate compressed foam, a peristaltic pump delivers chloroxylenol disinfectant, and a PTC heater with fan dries everything before the user retrieves their helmet.

A dual-sensor interlock — active IR proximity on GPIO 33 and a door-mounted magnetic reed switch on GPIO 19 — ensures that if the door opens mid-cycle, every relay cuts within 1 ms. A pilot study on five Bengaluru commuter helmets achieved mean bacterial reduction of  $94.52 \pm 0.48\%$  ( $t(4) = 7.03$ ,  $p = 0.002$ , Cohen's  $d = 3.14$ ) and approximately 87.2% fungal reduction.

**Index Terms** - helmet sanitization, ESP32, IoT, Firebase, automated cleaning, antimicrobial, ultrasonic mist, finite state machine, real-time telemetry, rider hygiene, smart kiosk.

## I. INTRODUCTION

Road crashes kill roughly 1.35 million people each year worldwide, and motorcycle or three-wheeler riders account for about 28% of that toll [1]. Wearing a helmet cuts personal death risk by around 42% [2], which is why mandatory helmet laws are standard in most countries. But helmets introduce a hygiene problem that almost nobody talks about.

The issue is not that riders are careless — it is that washing a helmet is genuinely inconvenient. You have to pull out the liner, hand-wash it, and then wait hours for the padding to dry. Unsurprisingly, a pan-India survey found

that 73% of riders clean their helmet liners less than once a month [6]. So the open-cell polyurethane foam inside keeps absorbing sweat, sebum, and dust from every single ride.

That creates a warm, moist, nutrient-saturated environment that functions almost like a petri dish. Swab cultures from regularly-used helmets routinely turn up *Staphylococcus aureus*, *Propionibacterium acnes*, and dermatophytic fungi [3]. Extended contact causes acne mechanica, scalp folliculitis, and contact dermatitis [4], [19].

HygieHelm was our attempt to remove every friction point from helmet cleaning. The design goal was simple: put your helmet in, close the door, take your candy, and collect a clean dry helmet six minutes later.

### A. Why This Needs an Automated Solution

Three factors make manual cleaning inadequate. First, tropical and humid climates accelerate microbial growth dramatically compared to temperate regions [5], making regular cleaning even more critical for the majority of the world's commuters. Second, a kiosk at a fuel station removes the time barrier entirely — cleaning happens while the rider does something else anyway. Third, public parking lots and fuel stations already have power outlets and regular footfall, so no new infrastructure is needed.

### B. Key Contributions

This paper covers hardware design, firmware architecture, and biological testing of HygieHelm. Specific contributions include: (1) a working kiosk from off-the-shelf components for under USD 52; (2) pilot validation on five helmets achieving  $94.52 \pm 0.48\%$  mean bacterial reduction ( $p = 0.002$ , Cohen's  $d = 3.14$ ); (3) a dual-sensor safety interlock shutting down within 1 ms of door opening; (4) a non-blocking FSM firmware using millis()-based timers; (5) Firebase real-time telemetry logging; and (6) a candy dispenser pilot feature intended as a behavioral reinforcement mechanism, to be empirically validated in a planned 20-person user study [25].

## II. LITERATURE REVIEW

### A. Microbial Load in Helmet Interiors

The microbial situation inside a regularly-used helmet is not subtle. Kulthanan et al. surveyed 120 commuter helmets in Bangkok and identified *S. aureus* in 38% of samples and coagulase-negative staphylococci on 72% of liners [7]. Research from North India reported mean colony densities around  $2.4 \times 10^4$  CFU/cm<sup>2</sup> [3]. Those numbers are directly linked to scalp conditions including acne mechanica, folliculitis, and seborrheic dermatitis [4], [17].

Existing decontamination approaches each have awkward trade-offs. UV-C light kills surface pathogens well but physically cannot penetrate the deep pores of open-cell foam at standard irradiance levels [8]. Ozone gas sanitizes effectively but degrades polystyrene shells over repeated exposure [9]. Chloroxylenol-based sprays show strong antimicrobial action against skin pathogens while remaining chemically benign to polyurethane liners [10], [18]. Ultrasonic misting creates droplets under 5  $\mu$ m — small enough to behave like a gas and diffuse deep into foam rather than pooling on the surface [11], [20].

The ESP32 has become the default platform for low-cost IoT public health applications, powering touchless sanitizer dispensers [12], [16], environmental sensors [13], and occupancy monitors [14], [22]. Its dual-core Xtensa LX6 processor, native Wi-Fi/Bluetooth, and sub-USD 5 price point make it practical for unattended kiosk deployments [15], [26].

### B. Cloud Telemetry in Embedded Kiosks

For single-device embedded deployments, Firebase Realtime Database has emerged as a practical alternative to MQTT broker architectures. Because Firebase exposes a low-latency REST API, a device can write telemetry directly to cloud storage without maintaining a separate message broker, reducing both cost and complexity [29]–[31].

### C. Gap in the Literature

While individual sanitization methods have been studied on flat textiles and hard surfaces, no prior system has combined them in a sequential, sensor-gated pipeline designed specifically for the complex porous geometry of helmet foam liners. That specific combination — physical extraction, mist pre-wetting, chemical spray, and convective drying — is what this paper presents.

## III. SYSTEM ARCHITECTURE

### A. Physical Layout

HygieHelm is a floor-standing cabinet measuring 400 mm  $\times$  450 mm  $\times$  900 mm. The front-hinged door opens to a foam-padded cradle where the helmet sits during cleaning. The user-facing panel has an LCD for cycle progress, a QR code area for payment processing, and a low-mounted chute that dispenses a reward candy at the start of each session.



Fig. 1. HygieHelm prototype — CAD render of the floor-standing kiosk enclosure (400 mm  $\times$  450 mm  $\times$  900 mm). Left panel (front): LCD display, QR payment panel, and candy dispense chute. Centre: front-hinged door with viewing window and helmet cradle. Lower right: exhaust grille with polypropylene filter.

### B. Bill of Materials

Table I lists every component in the prototype. Total build cost came to USD 51.50.

TABLE I BILL OF MATERIALS (BOM)

Component	Specification	USD
ESP32 DevKit V1	Dual-core, 240 MHz, Wi-Fi	4.50
IR Proximity Sensor	Active IR, 2–30 cm, GPIO 33	1.20
Reed Switch	NO type, GPIO 19	0.80
4-Ch. Relay Module	5V, optocoupler-isolated	3.50
Ultrasonic Mist Maker	1.7 MHz, 400 mL/h	6.00
Mini Vacuum Motor	12V DC, 8000 RPM	5.50
Dettol Spray Pump	Peristaltic, 12V DC	4.00

Hot Air Dryer	PTC heater + fan, 12V	7.00
SG90 Servo Motor	180°, 1.8 kg·cm	2.00
Power Supply	12V / 5A SMPS	6.00
Enclosure & Frame	Sheet metal + 3D-printed	8.00
Miscellaneous	Wiring, connectors, tubing	3.00
<b>Total</b>		<b>~51.50</b>

### C. Circuit Design

The ESP32 operates at 3.3V logic and drives four actuators through optocoupler-isolated relays connected to GPIO pins 14, 27, 25, and 32. Optoisolation separates the microcontroller from the noisy 12V power lines of the vacuum motor, mitigating transient spikes that would otherwise cause device resets. The relay board uses active-low logic, so a LOW on the control pin switches the load on.

The IR proximity sensor on GPIO 33 pulls LOW when a helmet is within its 5–15 cm range. The reed switch connects specifically to GPIO 19 because input-only pins (34, 35, 36, 39) do not support configurable internal pull-ups — using INPUT\_PULLUP on those pins leaves them floating. GPIO 19 uses the ESP32's internal pull-up, holding the pin HIGH when the door is open. When the door closes, the magnet aligns and pulls the pin LOW to confirm the seal. The SG90 servo on GPIO 18 receives a PWM signal from 500 to 2400  $\mu$ s to prevent mechanical stall at movement boundaries [23].

## IV. CLEANING CYCLE PROTOCOL

The cycle will not start unless both sensors confirm readiness simultaneously — the IR sensor must detect a helmet (GPIO 33 LOW) and the door must be confirmed shut (GPIO 19 LOW). Table II shows the four-stage sequence.

**TABLE II CLEANING CYCLE STAGES AND TIMING**

Stg	Operation	Duration	Purpose
0	Candy Dispense	15 s	Behavioral reward
1	Vacuum	60 s	Debris removal
2	Water Mist	90 s	Interior moistening
3	Dettol Spray	45 s	Antimicrobial treatment
4	Hot Air Dryer	150 s	Evaporation & drying
	<b>Total</b>	<b>360 s</b>	

### A. Stage 0: Candy Dispense

Once both sensors confirm readiness, the system waits ten seconds to let the user step back. The SG90 servo rotates from 0° to 90°, holds open for three seconds to drop a candy into the chute, then returns to 0°. This immediate reward on every visit is intended to reinforce the habit of regular use.

### B. Stage 1: Vacuum Extraction

A 12V, 8000 RPM motor runs for a full 60 seconds, drawing air through the helmet's ventilation channels and back through the foam liner. Open-cell polyurethane with 300–600  $\mu$ m pore size holds onto particulate matter — hair, skin flakes, accumulated dust — fairly stubbornly. Shorter vacuum cycles left visible debris behind in early tests, so the full minute was found to be necessary.

### C. Stage 2: Ultrasonic Water Mist

A 1.7 MHz ultrasonic transducer runs for 90 seconds, producing a mist of water droplets smaller than 5  $\mu$ m. At that size, droplets behave more like a gas than a liquid — they diffuse into the multi-layered padding rather than condensing on the outer surface [27]. This dissolves salt crystals from dried sweat and pre-wets the foam so that the disinfectant spray in the next stage absorbs evenly rather than beading off.

### D. Stage 3: Antiseptic Spray

A 12V peristaltic pump operates for 45 seconds, pushing a 4.8% w/v chloroxylenol solution through a multi-nozzle manifold angled to hit the cheek pads and crown lining directly. Chloroxylenol disrupts microbial cell membranes [10], and the 45-second contact window was sufficient to achieve target reduction rates without leaving skin-irritating residue [24].

### E. Stage 4: Hot Air Drying

The final 150 seconds activate a PTC ceramic element paired with a centrifugal fan, blowing warm air at 45–55°C across all helmet surfaces. This is the longest stage because open-cell polyurethane foam holds moisture stubbornly [21]. The warm airflow evaporates residual moisture, the elevated temperature boosts chloroxylenol efficacy, and the rider receives a helmet that is immediately wearable.

## V. FIRMWARE IMPLEMENTATION

### A. Non-Blocking FSM Architecture

The control firmware (v1.1) is written in C++ using the Arduino-ESP32 framework. An earlier version used sequential blocking delay() calls — a common embedded pitfall that freezes the CPU during active stages, preventing sensor monitoring or response to safety events [32]. Version 1.1 replaces those with a non-blocking FSM driven by millis()-based software timers.

The FSM moves through nine states: IDLE, CANDY\_WAIT, CANDY\_OPEN, CANDY\_CLOSE, VACUUM, MIST, DETTOL, DRYER, and COMPLETE. On every transition, a reference timestamp is recorded. The main superloop runs at ~1 kHz and checks the reed switch pin on each iteration. If that pin reads HIGH while a cycle is running — meaning the door magnet is no longer grounding

the pull-up — every relay goes off within 1 ms and the FSM returns to IDLE.

### B. Safety Interlocks

Four safety layers are implemented in firmware: (1) Pre-cycle gate: no actuator can energize unless both sensors simultaneously read LOW. (2) Mid-cycle monitoring: the door pin is checked on every loop iteration; a HIGH reading triggers emergencyShutdown(), cutting all relays and resetting the FSM. (3) Cycle lock flag: cycleRunning prevents duplicate trigger events from restarting an active cycle. (4) Boot-glitch prevention: the initialization routine writes all relay control pins HIGH before calling pinMode(OUTPUT), preventing the brief relay chatter that can occur when pins float during boot.

### C. Firmware Listing

Listing 1 presents key firmware sections. Complete source is on GitHub [33].

```
#define IR_PIN 33 // LOW=helmet present
#define REED_PIN 19 // LOW=door closed
#define RELAY_VACUUM 14 #define RELAY_MIST 27
#define RELAY_DETTOL 25 #define RELAY_DRYER 32

enum State { IDLE, CANDY_WAIT, CANDY_OPEN, CANDY_CLOSE, VACUUM, MIST, DETTOL, DRYER, COMPLETE };

void emergencyShutdown() {
  allRelaysOff(); candyServo.write(0);
  cycleRunning=false; enterState(IDLE);
}

void loop() {
  if(cycleRunning && digitalRead(REED_PIN)==HIGH)
  { emergencyShutdown(); return; }
  // state switch cases ...
}
```

Listing 1. HygieHelm FSM Firmware v1.1 (key sections).

## VI. EXPERIMENTAL EVALUATION

To verify whether the kiosk works as intended, we ran a pilot study on five full-face helmets ( $n = 5$ ) collected from daily commuters in Bengaluru. We acknowledge upfront that five helmets does not support broad generalization — this was a proof-of-concept run designed to check operational viability and generate an effect size for powering a larger follow-up trial. A prospective sample size calculation using G\*Power 3.1 (paired t-test, one-tailed,  $\alpha = 0.05$ ,  $1 - \beta = 0.95$ ) at the observed Cohen's  $d = 3.14$  indicates that  $n = 5$  provides 97.3% statistical power for detecting an effect of this magnitude, confirming that the current sample

is adequate for the proof-of-concept objective. Nevertheless, the absolute sample is insufficient for generalization across helmet types and user demographics; a follow-up study targeting  $n = 50$  across full-face, open-face, and modular helmet categories is planned for Q3 2025, with results expected by Q1 2026. Expanding to 50 helmets will let us evaluate performance across different styles, user profiles, and climate conditions.

All five helmets were 6–18 months old, none cleaned in at least a month before testing. To establish a control baseline, we swabbed a marked area, left the helmet untouched for exactly six minutes, then swabbed the same spot again — this isolated the treatment effect from normal swab-to-swab variation.

### A. Swabbing Protocol

Sterile cotton swabs moistened in phosphate-buffered saline (PBS) were rubbed over a 4 cm<sup>2</sup> marked zone on both the cheek pad and crown liner. Swabs were plated immediately onto nutrient agar (bacteria) and blood agar (fungi). Post-cycle swabs came from the same marked zones within two minutes of the dryer stage finishing. Plates incubated at 37°C — 24 h for bacteria, 48 h for fungi. CFU counts were performed by two independent observers and averaged.

### B. Statistical Methods

Descriptive statistics (mean, SD) were computed in Microsoft Excel. A paired two-tailed t-test compared pre- and post-treatment CFU counts, with Cohen's  $d$  as the paired effect size estimator. A 95% confidence interval was derived from the t-distribution at  $df = 4$ . Significance threshold:  $\alpha = 0.05$ .

### C. Bacterial Reduction Results

Table III shows CFU counts before and after treatment for each helmet.

**TABLE III BACTERIAL CFU/CM<sup>2</sup> BEFORE AND AFTER HYGIEHELM TREATMENT (N = 5, PILOT STUDY)**

Helmet	Pre (CFU/cm <sup>2</sup> )	Post (CFU/cm <sup>2</sup> )	Red. (%)
H1	18,400	1,020	94.5
H2	24,600	1,180	95.2
H3	12,800	780	93.9
H4	31,200	1,640	94.7
H5	22,000	1,250	94.3
<b>Mean</b>	<b>21,800</b>	<b>1,174</b>	<b>94.52</b>
SD	6,870	317	0.48

Paired two-tailed t-test:  $t(4) = 7.03$ ,  $p = 0.002$ . 95% CI on mean reduction: [93.92%, 95.12%]. Cohen's  $d = 3.14$  (very large effect).

#### D. Fungal Reduction Results

Blood agar plates incubated for 48 hours showed visible fungal colonies on all five helmets prior to treatment. Table IV shows colony counts before and after a single cycle.

**TABLE IV FUNGAL CFU/CM<sup>2</sup> BEFORE AND AFTER HYGIEHELM TREATMENT (N = 5, PILOT)**

Helmet	Pre (CFU/cm <sup>2</sup> )	Post (CFU/cm <sup>2</sup> )	Red. (%)
H1	420	52	87.6
H2	580	71	87.8
H3	240	35	85.4
H4	760	95	87.5
H5	490	63	87.1
<b>Mean</b>	<b>498</b>	<b>63.2</b>	<b>87.2</b>
SD	185	21.4	0.95

A paired two-tailed t-test on the fungal CFU data yielded  $t(4) = 6.18$ ,  $p = 0.003$ , 95% CI on mean reduction [85.7%, 88.7%], Cohen's  $d = 2.76$  (very large effect). These results are consistent with the bacterial findings and confirm that the full four-stage cycle reduces fungal load substantially. However, given the limited sample size ( $n = 5$ ) and that fungal culture methods carry higher inter-observer variability than bacterial plate counts, the fungal results should be treated as exploratory pending a larger validation study. No statistical comparisons are made between fungal and bacterial reduction rates.

#### E. Control Group Comparison

Table V reveals the most telling comparison: chloroxylenol spray alone achieved 62.4% bacterial reduction, while the complete four-stage cycle reached 94.52% — a gap of roughly 32 percentage points. That difference quantifies the added contribution of vacuum pre-cleaning, ultrasonic pre-wetting, and thermal drying, none of which involve disinfectant chemistry at all.

**TABLE V MEAN BACTERIAL CFU REDUCTION — THREE CONDITIONS (N = 5)**

Condition	Mean Red.(%)	SD(%)
No treatment (control)	3.2	1.8
Chloroxylenol spray only	62.4	5.1
<b>HygieHelm full 4-stage cycle</b>	<b>94.52</b>	<b>0.48</b>

#### F. Power Consumption

Table VI breaks down power draw per stage based on rated component specifications. Per-cycle energy totals 1.88 Wh. At a commercial electricity rate of INR 8/kWh, each

cycle costs under INR 2 ( $\approx$  USD 0.015). Running 50 cycles/day keeps daily electricity cost under INR 100.

**TABLE VI POWER CONSUMPTION PER CLEANING STAGE (CALCULATED FROM RATED SPECIFICATIONS; MEASURED VALUES TO BE REPORTED IN V2)**

Stage	Dur.	V	I	Energy (Wh)
Vacuum	60 s	12V	1.2A	0.240
Mist	90 s	12V	0.8A	0.240
Dettol Spray	45 s	12V	0.5A	0.075
Dryer	150 s	12V	2.5A	1.250
ESP32	360 s	5V	0.15A	0.075
<b>Total</b>	<b>6 min</b>			<b>1.880 Wh</b>

### VII. KIOSK DESIGN AND USER INTERACTION

#### A. Mechanical Construction

The outer shell is 1.2 mm powder-coated mild steel. Internal brackets for the vacuum motor, mist reservoir, and pump were 3D-printed in PETG, chosen for its resistance to chloroxylenol solutions. The front door uses a magnetic latch with the reed switch on GPIO 19 positioned so the circuit closes only when fully pressed shut. Overall dimensions: 400 mm (W)  $\times$  450 mm (D)  $\times$  900 mm (H). Helmet clearance supports sizes S–XXL (head circumference  $\leq$  63 cm). A 150 mm  $\times$  150 mm toughened glass viewing window and an 80 mm exhaust grille with washable polypropylene filter complete the enclosure.

#### B. User Flow

The user interaction sequence proceeds as follows: (1) Rider scans the QR code on the front panel to initiate payment. (2) Rider opens the door and places the helmet on the foam cradle. (3) Rider closes the door until the magnetic latch engages. (4) LCD displays 'Sensors OK — Starting in 10 s' once both sensors confirm readiness. (5) Candy is dispensed into the chute as the cycle begins; rider steps back. (6) LCD updates stage progress throughout the 360-second cycle. (7) Upon completion, LCD reads 'Done — Helmet Ready' and the buzzer sounds twice. (8) Rider retrieves the sanitized and dry helmet.

### VIII. IOT TELEMETRY AND REMOTE MONITORING

#### A. Architecture

The design assumes fleet deployment across fuel stations and parking lots, monitored centrally without physical site checks. The ESP32's built-in Wi-Fi connects to Firebase Realtime Database over HTTPS using a REST API [29]. At the end of each cycle or emergency abort, the `logCycleToFirebase()` function posts a JSON payload containing a monotonically increasing `cycle_id`, a boot-

relative timestamp\_s, a boolean completed flag, and a nominal duration\_s of 360 seconds.

### B. Offline Resilience

If Wi-Fi drops during cycle completion, the telemetry function detects this via a non-blocking `WiFi.status()` check and exits immediately — it does not block the FSM or delay the user. For v1.2, we plan to implement a SPIFFS-backed local buffer that queues failed logs and uploads them when connectivity returns.

### C. Dashboard

The Firebase console and companion Android app display daily and weekly cycle counts, abort rates (useful for spotting door sensor failures or tampering patterns), and a per-device last-seen heartbeat timestamp. Version 1.2 will add reservoir level sensors to push low-fluid alerts to operators.

## IX. DISCUSSION

### A. Comparison with Alternative Methods

A  $94.52 \pm 0.48\%$  mean bacterial reduction compares well against existing alternatives. Table VII summarizes the comparison. UV-C cabinets can hit 90–99% on hard flat surfaces under controlled lab conditions, but that performance collapses on porous foam because UV-C cannot physically penetrate it [8]. Manual washing achieves 70–85% but demands 4–8 hours and liner disassembly. HygieHelm matches UV-C performance on the metric that matters most — actual foam decontamination — in a fraction of the time.

**TABLE VII COMPARATIVE SANITIZATION PERFORMANCE**

Method	Bacterial Red.	Foam Pen.	Time
UV-C Cabinet	90–99%*	Poor	10–20 min
Manual Wash	70–85%†	Good	4–8 h
<b>HygieHelm</b>	<b>94.52±0.48%</b>	<b>Good</b>	<b>6 min</b>

\*On flat hard surfaces under lab conditions [8]. †Estimated from literature; no helmet-specific controlled study found.

### B. Why Six Minutes Matters

Our preliminary surveys consistently showed that the primary reason riders skip helmet cleaning is drying time, not the scrubbing effort itself. A helmet that goes into a kiosk and comes out dry and wearable in six minutes — roughly the time it takes to fill a tank and pay — removes that barrier entirely. That behavioral dimension matters as much as the microbiology.

### C. Limitations

Several limitations need addressing before commercial deployment. The  $n = 5$  pilot is too narrow for broad generalization, even with a strong effect size. Only full-face

helmets were tested; open-face, half-face, and modular designs have different internal geometries that may not receive uniform spray coverage. Long-term material compatibility data is missing — we do not yet know whether repeated chloroxylenol exposure and convective heating affect foam density or strap integrity over hundreds of cycles. The candy dispenser's behavioral effectiveness is assumed, not measured. Power figures come from component datasheets, not direct clamp meter measurements under dynamic load.

## X. FUTURE WORK

The most immediate priority is scaling validation to at least 50 commuter helmets across modular, open-face, and half-face categories, with Wilcoxon signed-rank tests and ANOVA across subgroups. Direct head-to-head comparisons against UV-C cabinets and manual washing on the same helmet set are planned. Material degradation testing will expose helmets to 20 consecutive cleaning cycles, then measure foam density, strap tensile strength, and outer shell hardness (Shore D).

Firmware v1.2 will transition to a FreeRTOS multitasking architecture with isolated tasks for sensor polling, LCD updates, and database logging, plus SPIFFS-backed offline buffering. The current v1.1 firmware will be released under MIT license on GitHub [33].

Planned hardware enhancements include a DHT22 temperature and humidity sensor inside the chamber to dynamically extend drying time in 30-second increments, and a 275 nm UV-C LED array for a supplemental surface exposure step targeting pathogens less susceptible to chloroxylenol. A structured 20-person user study will measure repeat-use intention and test the candy dispenser's behavioral impact empirically [25].

## XI. CONCLUSION

HygieHelm is a functional proof-of-concept for automated helmet sanitization: a four-stage cleaning kiosk assembled from off-the-shelf hardware for under USD 52, running a non-blocking FSM firmware with Firebase telemetry, completing a full cycle for less than USD 0.02 in electricity.

In a five-helmet pilot, a single 6-minute run achieved  $94.52 \pm 0.48\%$  mean bacterial reduction ( $t(4) = 7.03$ ,  $p = 0.002$ , Cohen's  $d = 3.14$ ) and approximately 87.2% fungal reduction. The key technical contribution is that sequential combination of physical extraction, mist pre-wetting, chemical spray, and convective drying achieves genuine foam penetration — something surface-only methods like UV-C cabinets cannot do. The FSM safety architecture shuts everything down within 1 ms of a door-open event, and Firebase connectivity enables fleet-scale remote monitoring.

The pilot data is promising but limited. A larger study across helmet types and demographics is needed before any commercial rollout. That work is underway.

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