

Development of a Pesticide Spraying Station for Integration with the ANTRAC UGV

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Abstract

Anthrachnose constrains chili production, and calendar spraying applies the same volume regardless of disease condition or canopy size. ANTRAC, an AI-enabled unmanned ground vehicle (UGV) developed at IPB University, detects the disease but has no actuation endpoint. This research developed and tested that endpoint, a spraying station that converts a fruit-level disease index into a metered spray command through four auditable steps: canopy-volume estimation, index-based tank selection, dose calculation bounded by safety rails, and pump-time derivation. An ESP32 controller serves a WebSocket endpoint, selects one of three isolated tank paths, and drives a ten-nozzle boom. Firmware output matched manual calculation in all three tested scenarios. For the $300 \times 50 \times 80$ cm reference strip the lower rail raised the 75.2 mL raw dose to 180 mL, giving a 14.29 s command at 12.6 mL/s. Two hydraulic checks at the 560 mL command delivered 8.4–12.3% less liquid than commanded, locating the dominant error in the open-loop hydraulic path, not the arithmetic. The station held Wi-Fi association through 50 m on an obstructed path and accepted a spray command near -88 dBm. The tests establish station-side functional readiness, not closed-loop operation or agronomic efficacy.

Keywords: canopy-volume dosing, chili anthracnose, ESP32, unmanned ground vehicle, variable-rate application

INTRODUCTION

Researchers at IPB University developed ANTRAC as an AI-enabled unmanned ground vehicle (UGV) for detecting anthracnose in chili and supporting integration with a fungicide applicator (IPB TV, 2025; IPB University, 2025; Ridwan Siskandar, 2025), continuing an earlier line of low-cost sensing-to-actuation machinery for Indonesian smallholders (Siskandar, Dio, Alatas, & Irzaman, 2022; Siskandar, Santosa, Wiyoto, Kusumah, & Hidayat, 2022). Its detector labels each fruit as symptomatic or non-symptomatic, and the fruit-level disease index supplied to the spraying station is the proportion of detected fruit carrying visible lesions.

Anthrachnose is one of the most destructive diseases of chili (*Capsicum* spp.) in tropical production. Several *Colletotrichum* species are associated with anthracnose of *Capsicum* in Asia (De Silva et al., 2021), and severe epidemics have caused yield losses of up to 84% (Anand, Gupta, & Chourasia, 2020). Infections can also remain quiescent on apparently healthy fruit until ripening or storage, a life-cycle trait of the genus (De Silva, Crous, Ades, Hyde, & Taylor, 2017), which complicates decisions based only on visible symptoms (De Silva et al., 2021).

Growers therefore tend to spray on a calendar, applying the same formulation and volume across a field regardless of disease condition or canopy size, although condition-based decision support has already reduced anthracnose sprays without loss of control in strawberry (Cordova, Madden, Amiri, Schnabel, & Peres, 2017). Repeated exposure contributes to fungicide resistance selection (Corkley, Fraaije, & Hawkins, 2022), while real-time precision spraying can reduce application (Zanin et al., 2022). Both matter when farmers rotate several active ingredients to maintain control (Fauzi, Syaefullah, Dwitama, Deden, & Dukat, 2023; Padghan, Mondal, & Gade, 2023; Sathiyaseelan, Naher, Islam, & Mondal, 2024).

Canopy-proportional dosing was introduced through the tree-row-volume method (Manktelow & Praat, 1997). Laser and ultrasonic sensing later adapted spray output to canopy

geometry, covering both seasonal adjustment and real-time target spraying (L. Li et al., 2018; Nan, Zhang, Zheng, Yang, & Ge, 2023). Detection-driven target spraying has since coupled improved YOLOv5 inference to nozzle actuation in the field (H. Li et al., 2022).

Reviews of unmanned and variable-rate application document rapid platform development (Chen, Lan, Fritz, Hoffmann, & Liu, 2021; Hanif, Han, & Yu, 2022; Jiao et al., 2025; Taseer & Han, 2024), and convolutional neural networks can identify anthracnose and other chili diseases from images (Kanaparthi & Ilango, 2026; Kim, Yoon, & Ju, 2025), and the same architectures transfer to other crops (Shen et al., 2025). The same research group previously applied image processing for fruit maturity sorting (Siskandar et al., 2020) and built a CNN-based monitoring system for spraying machines using NVIDIA Jetson Nano and Arduino Mega, achieving 90% detection accuracy on the “Jajar Legowo” object (Siskandar, Mandang, Hermawan, & Irzaman, 2023). However, reviews of AI-based disease detection note that reported detector accuracy does not specify how a disease index becomes a transparent liquid command on reproducible smallholder hardware (Jafar, Bibi, Naqvi, Sadeghi-Niaraki, & Jeong, 2024).

Relative to the ANTRAC detection and navigation subsystem reported by (IPB TV, 2025; IPB University, 2025; Ridwan Siskandar, 2025), the actuation-side hardware-software stack previously established for agricultural spraying machines (Siskandar et al., 2023; Siskandar, Mandang, Hermawan, & Irzaman, 2025) and image-processing-based fruit-sorting machinery (Siskandar et al., 2020) forms the technological foundation for the station developed here. This research develops the downstream station: input handling, firmware, a four-step dose routine, three isolated tank paths, hydraulic and nozzle hardware, and local status display. The contribution of this study is the actuation-side counterpart: a transparent disease-index-to-dose conversion whose intermediate values are all inspectable, safety rails that bound the commanded volume, and three-tank selection that can support active-ingredient rotation on commodity hardware. The station is therefore reported as a developed subsystem rather than a fully integrated ANTRAC system. The scope ends at station-side acceptance and execution of ANTRAC-compatible messages. Live UGV coupling, detector validation, field deposition, disease suppression, and pesticide savings remain outside the reported evidence. ANTRAC is therefore the integration target rather than a tested subsystem, and the results reported here were obtained at the spraying station with ANTRAC messages emulated by a browser dashboard.

METHODS

This research followed an engineering design cycle that covered requirements analysis, hardware and software design, integration, and functional testing. Figure 1 presents the resulting architecture as four sequential layers.

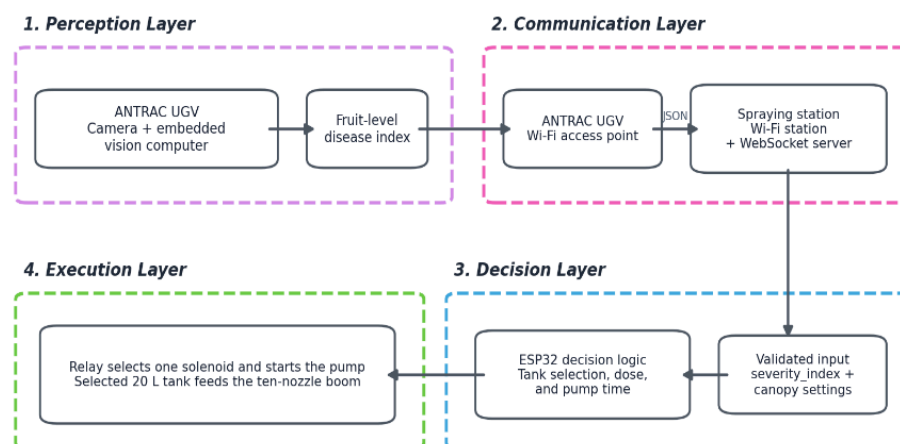


Figure 1. Four-layer system architecture.

The Perception Layer produces a fruit-level disease index on ANTRAC, the Communication Layer transfers it through Wi-Fi and WebSocket, the Decision Layer validates the input and calculates

the tank, dose, and pump time, and the Execution Layer converts that decision into a selected liquid path and nozzle output.

The requirements were fixed at the start of the design cycle. The station must accept a disease index from ANTRAC over the local network, reject malformed or out-of-range input, derive a tank, a volume, and a pump time from that index and the configured canopy, actuate one liquid path at a time, and return to idle without a manual reset. Non-functionally, computation and traffic must remain on the local network, the control loop must stay responsive while the pump runs, configuration must survive a power cycle and be editable without re-flashing, and every valve must be shut in its de-energized state. These requirements set the acceptance criteria applied in the functional tests.

a) Perception Layer

Within the Perception Layer, upstream processing on ANTRAC combines detections into the index sent to the station. Figure 2 presents representative detections for the anthracnose and non-anthracnose classes, and the firmware calls the input *severity_index*.

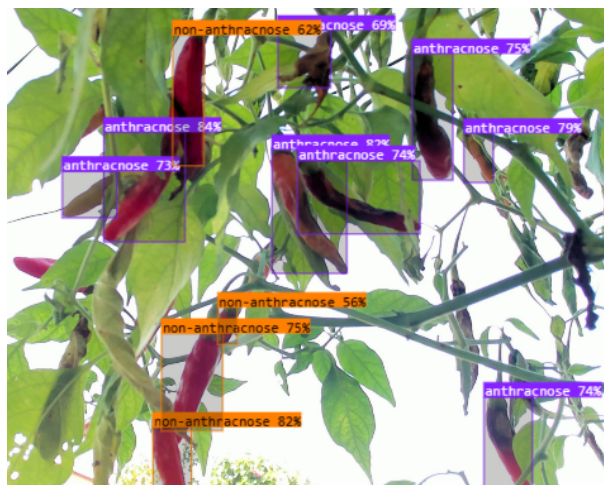


Figure 2. Representative bounding-box detections for anthracnose and non-anthracnose chili fruits, with class labels and confidence scores.

Disease severity expresses the proportion of affected tissue on one sampling unit, whereas disease incidence expresses the proportion of units classified as diseased (Bock, Chiang, & Del Ponte, 2022; Bock, Pethybridge, et al., 2022). The input expresses the proportion of detected fruits classified as symptomatic, so it corresponds more closely to fruit-level incidence, and *severity_index* is retained only because the firmware and message schema use that name.

b) Communication Layer

The Communication Layer connects the station to the 2.4 GHz access point hosted by the ANTRAC UGV. The ESP32 operates as a Wi-Fi station and serves WebSocket at a static address, with agrispray.local as its mDNS hostname. A spray message carries an *action* and a numeric *severity_index* in JSON format. The browser dashboard emulated ANTRAC with the same message structure during validation. The controller then passes accepted input to the Decision Layer. The message-relay approach follows the Jetson Nano-Arduino wireless monitoring framework established for spraying machines (Siskandar et al., 2023). Figure 3 presents the operational topology.

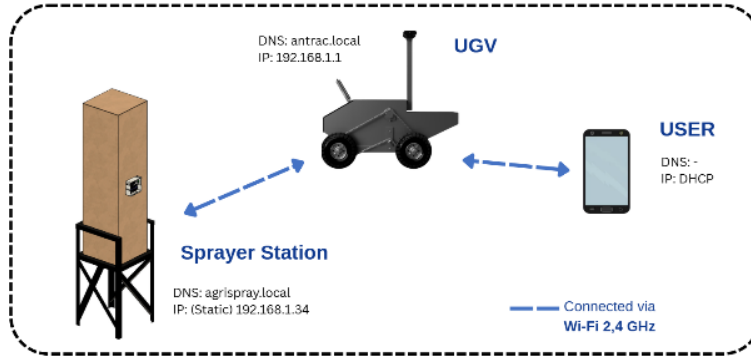


Figure 3. Operational Wi-Fi topology.

c) Decision Layer

The Decision Layer converts each accepted input into a reproducible hydraulic command through the four steps shown in Figure 4. Step 1 calculates canopy volume from the stored strip length (L), treated width (W), and plant height (H), Step 2 maps the index to standby or to tanks T1, T2, and T3, Step 3 multiplies canopy volume by the dose coefficient and applies the volume limits, and Step 4 divides the final volume by total flow to obtain pump time. The index chooses the formulation path but does not scale the volume.

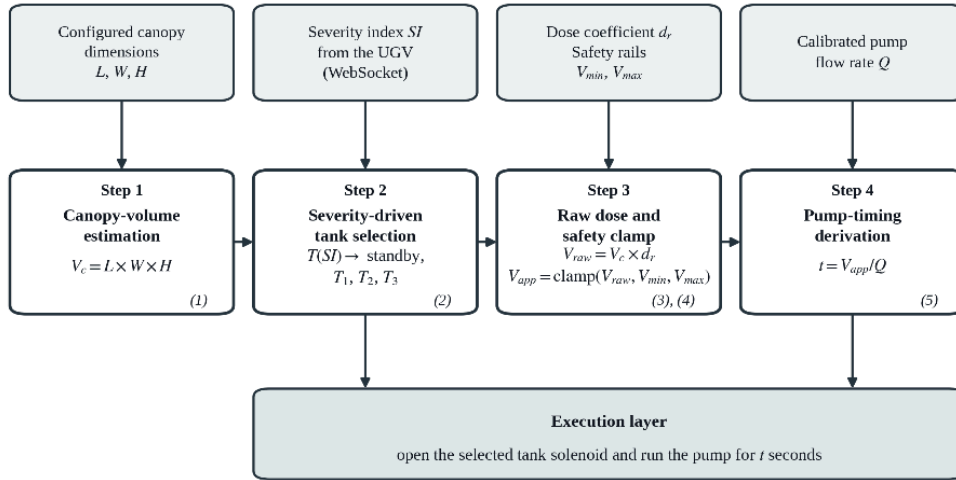


Figure 4. Four-step station-side dose computation from configured canopy dimensions and received disease index to tank and pump commands.

$$V_c = L \times W \times H \quad (1)$$

Equation (1) computes the canopy volume of one treated strip, V_c in cm^3 , from three configuration inputs: the strip length L along the plant row, the treated width W covered by one spray pass, and the configured plant height H measured from the ground to the canopy top, all in cm . V_c is therefore the bounding volume of the treated strip rather than the foliage volume alone, and that envelope is the dosing basis, following the canopy-volume convention of Nackley et al. (2021) and the canopy-characteristic dose models compared by (Zhou, Xue, Chen, Cai, & Jiao, 2023).

$$T(SI) = \{\text{standby if } SI \leq 5\%; \quad T_1 \text{ if } 5\% < SI \leq 25\%; \quad T_2 \text{ if } 25\% < SI \leq 45\% \quad (2)$$

Equation (2) maps the received disease index SI , in percent, to the selected tank slot $T(SI)$. The four states are mutually exclusive and cover the full range, with an index at or below 5% holding the station in standby and the three higher bands selecting T1, T2, or T3. The severity index therefore selects the formulation path while the configured canopy fixes the volume, so the station implements canopy-proportional dosing with severity-gated tank selection rather than continuous, severity-driven volume modulation.

$$V_{raw} = V_c \times d_r \quad (3)$$

Equation (3) converts canopy volume into the raw spray volume V_{raw} in mL through the dose coefficient d_r , the spray volume applied per unit canopy volume, in mL cm^{-3} . This research adopted $d_r = 6.27 \times 10^{-5} \text{ mL cm}^{-3}$ from the variable-rate setting reported by Nackley et al. (2021) and did not calibrate it for chili, so V_{raw} is a reproducible starting point rather than a validated agronomic dose. The coefficient is a canopy-volume convention rather than a chili-specific calibration, since it scales the applied volume with the canopy envelope, so its transfer to chili is a transparent geometric default that can be re-trimmed on the station rather than an agronomically validated dose for this crop.

$$V_{app} = \min(\max(V_{raw}, V_{min}), V_{max}) \quad (4)$$

Equation (4) clamps the raw volume between two safety rails to obtain the applied volume V_{app} in mL. The lower rail V_{min} of 180 mL guards against a command too small to wet the canopy or to prime the line, and the upper rail V_{max} of 560 mL bounds run-off and tank consumption. Both rails are operational bounds derived from bench observation of the ten-nozzle line at the calibrated flow rate, not crop-tolerance limits, and both are stored as reconfigurable parameters.

$$t = \frac{V_{app}}{Q} \quad (5)$$

Equation (5) converts the applied volume into the pump run time t in seconds by dividing V_{app} by the calibrated total flow rate Q in mL s^{-1} , obtained over a 60 s pump run. Run time, not volume, is the quantity the firmware actually controls, so any change in nozzle condition that shifts Q requires re-calibration.

Step 1 depends entirely on stored geometry, because canopy dimensions are configuration inputs rather than sensor measurements. Figure 5 presents the reference strip of $300 \times 50 \times 80 \text{ cm}$ along a plant row, where L is the travel-direction length, W the treated width between the frame legs, and H the configured plant height. A standard chili bed is approximately 100 to 125 cm wide and carries two rows, so the 50 cm machine lane corresponds to one pass rather than the whole bed.

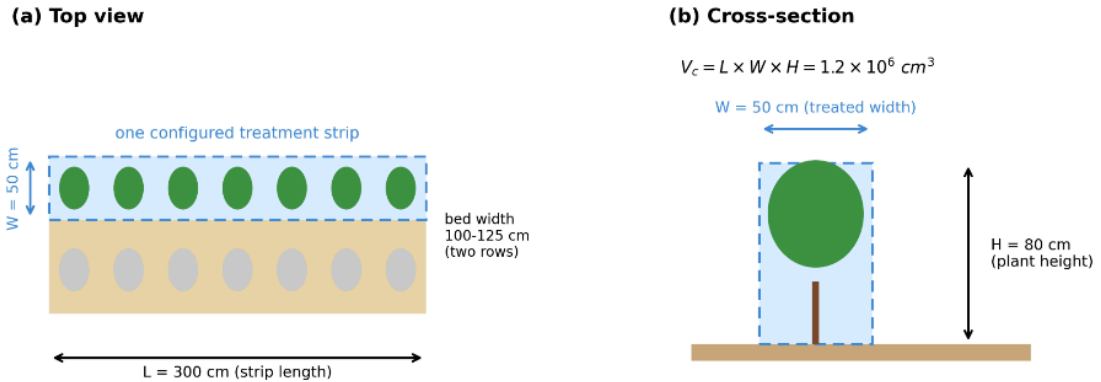


Figure 5. Reference treatment strip used to configure canopy volume: (a) top view and (b) cross-section, with consistent L , W , and H notation.

Step 2 applies Equation (2), which maps the index into four mutually exclusive states, as Table 1 presents. The separate tank and valve paths allow a different formulation per class, but this research prescribed no fungicide and evaluated no rotation schedule, and all tanks contained water during testing.

Table 1. Index thresholds and station tank-selection rules

Severity index (%)	Status	Active tank	Function
≤ 5	Standby	None	No spray
$> 5-25$	Mild	T1	Formulation slot 1
$> 25-45$	Moderat	T2	Formulation slot 2

Steps 3 and 4 rest on two numerical inputs. The dose coefficient of 6.27×10^{-5} mL/cm³ converts the variable-rate setting of 0.06 fl oz per cubic foot of canopy reported by (Nackley et al., 2021), where canopy volume is width $\times$ height $\times$ row length. Pump flow was measured over 60 s by dividing the collected discharge by time, giving 12.6 mL/s for the calculation checks, and because cleaning a clogged nozzle changes the flow, the calibration was repeated for each nozzle state in the hydraulic checks, giving 12.5 and 12.7 mL/s.

d) Execution Layer

The Execution Layer converts the command into liquid output: the relay board starts the pump and opens the selected solenoid valve, one of three 20 L tank paths feeds the pump, and the ten-nozzle boom distributes the spray across the treatment strip.

Four functional procedures were performed. First, wireless association and RSSI were recorded at approximately 31, 39, 47, and 50 m along an obstructed outdoor path, with two readings at 47 m, and a boundary check at 65 m. Second, firmware outputs were compared with manual calculations from Equations (1) to (5) for index values of 15%, 35%, and 80% on the reference strip. Third, hydraulic delivery was checked at the 560 mL maximum command in two sequential conditions labelled before and after nozzle cleaning. A nozzle counted as clogged when its mist no longer formed a full 60° cone, and affected nozzles were cleaned by hand and re-observed until the cone recovered, after which the flow rate was calibrated again. Fourth, the dashboard emulated ANTRAC with *updateLogic* messages carrying the three index values, and tank selection, volume, duration, actuation, and return to IDLE were observed. Acceptance required exact agreement between firmware and manual calculations, association along the measured path, and at least one accepted command under weak signal. Biological efficacy, deposition, and live ANTRAC integration were not criteria.

RESULTS AND DISCUSSION

a) Realized Station

The prototype is built from three welded steel frames sized from standard chili cultivation practice. The Station Frame is a 500 $\times$ 500 $\times$ 2205 mm cabinet of 40 $\times$ 40 mm angle iron that carries three stacked 20 L tanks, and the Base Frame is a 600 $\times$ 400 $\times$ 500 mm structure of 60 $\times$ 60 mm hollow section with diagonal bracing that seats the pump. Steel was chosen over aluminum T-slot profile because three full tanks weigh approximately 60 kg. The Spray Frame is a 3000 $\times$ 550 $\times$ 1100 mm assembly of half-inch PVC pipe carrying ten misting nozzles at 32.5 cm spacing, which places the nozzle line 100 to 103 cm above ground. Figure 6 presents the assembled Spray Frame with its parts labelled.



Figure 6. Assembled spray boom with labelled parts: the 3000 mm boom, the ten misting nozzles at 32.5 cm spacing, a PVC support leg, and the feed line from the pump.

Control electronics are housed in a modular panel built around an ESP32-DEVKITC-32U with an external 19 cm 700 to 2700 MHz whip antenna, an eight-channel active-low relay module driving three 12 V solenoid valves and one 12 V brushless self-priming pump rated at 160 psi, and an LM2596 buck converter stepping 12 V to 5 V. A 0.96-inch OLED reports local state, a real-time clock time-stamps operations, and a buzzer signals mode changes.

All computation and traffic remain on the station's local network, and no cloud connection is required. The ESP32 has been applied as the monitoring and control node in agricultural enclosures (Bustomi, Riauwindu, Suhiyar, & Indarto, 2025), following an MQTT-based monitoring-station pattern reported in earlier agricultural monitoring work (Novianty, Ferdika, & Sholihah, 2019).

Figure 7 presents the wiring, where GPIO 14 drives the pump relay, GPIO 25, 26, and 27 drive the T1, T2, and T3 solenoid relays, GPIO 13 drives the buzzer, and GPIO 21 and 22 carry the I²C bus.

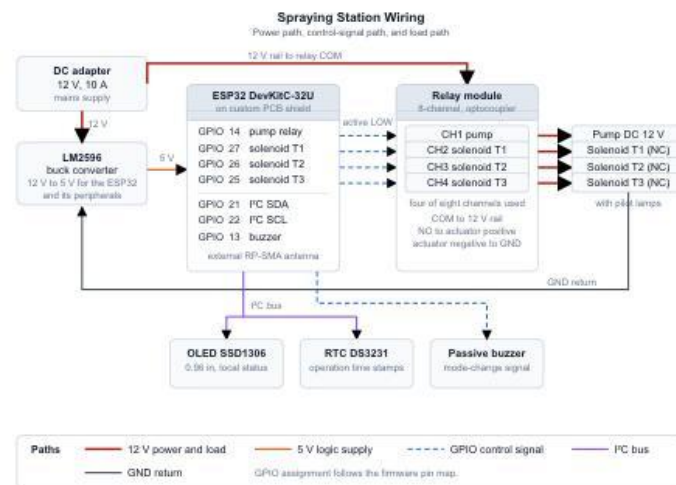


Figure 7. Station wiring: power paths, GPIO control signals to the relay module, and the switched load path to the pump and three tank solenoid valves.

The station firmware implements the design as a non-blocking state machine. It validates each incoming message, stores ten configuration parameters in non-volatile memory, exposes them to the local dashboard, and moves from IDLE to SPRAYING and back through elapsed-time checks rather than blocking delays. A stop command or the expiry of the calculated duration closes all three solenoids and stops the pump, and the station stays responsive to status and safety commands while

actuation proceeds. The realized station therefore meets the non-functional requirements stated above: computation and traffic stay on the local network, the control loop remains responsive while the pump runs, configuration survives a power cycle, and every valve is shut in its de-energized state.

b) Geometric Coverage of the Realized Boom

Nozzle geometry constrains the plant height that can be covered continuously. For a 60° cone, wetted diameter is 1.155 times the nozzle-to-canopy clearance, so adjacent patterns at 32.5 cm spacing begin to meet at a clearance of about 28 cm. Figure 8 presents the cone geometry, the nozzle-to-canopy clearance, and the plant height measured from the ground. With the nozzle line at 100 to 103 cm, uninterrupted geometric coverage reaches plant heights of roughly 72 to 75 cm, which is 5 to 13 cm below the 80 to 85 cm of stake left above ground by a 100 cm stake buried 15 to 20 cm (Balai Penerapan Standar Instrumen Pertanian Kalimantan Selatan, 2023). Raising the nozzle line to at least 108 cm would close this shortfall without changing the firmware, because frame height is not an input to the dose equation.

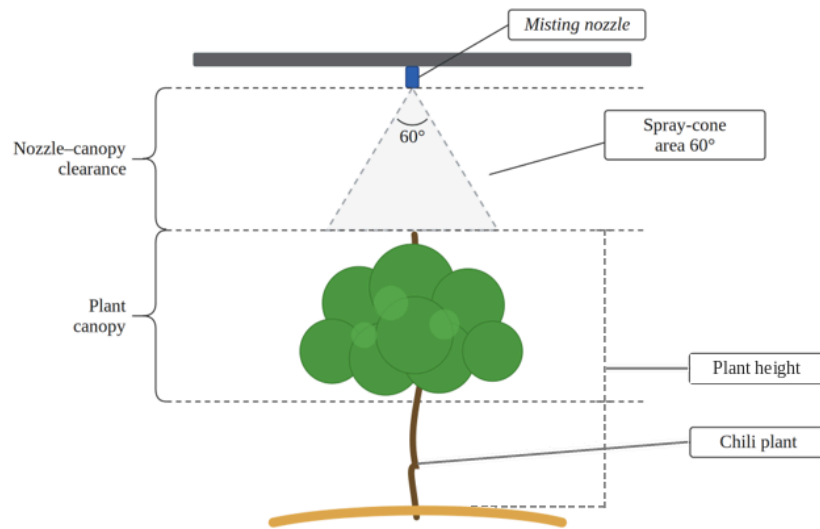


Figure 8. Geometry of the 60° nozzle cone, nozzle-to-canopy clearance, and configured chili plant height.

c) Functional Verification

Firmware computation agreed with the manual reference in all three tested spray scenarios, as Table 2 presents. With $L = 300$ cm, $W = 50$ cm, and $H = 80$ cm, canopy volume was 1.2×10^6 cm³ and the adopted coefficient produced a raw dose of 75.2 mL. Because that value fell below the 180 mL lower rail, the applied volume became 180 mL and pump duration 14.29 s at 12.6 mL/s. The 0.0% deviation verifies implementation of the stated equations, not the agronomic suitability of the coefficient or the rail. The identical volume across S1 to S3 is expected, because severity changes the tank path while the same configured canopy and active lower clamp produce the same volume. A geometric sensitivity check on Equation (3) locates where each rail stops governing. The lower rail holds the applied volume at 180 mL while the product of strip length and canopy height remains below about 5.7×10^4 cm², which at the 50 cm lane width corresponds to strip lengths up to 7.2 m at the configured 80 cm plant height, 9.6 m at 60 cm, and 5.7 m at 100 cm. The upper rail is reached only near 22 m at 80 cm, so across the single-pass strip lengths used here the applied volume is rail-limited rather than canopy-limited, and the reference strip would clear the lower rail only at a coefficient of about 1.5×10^{-4} mL cm⁻³, roughly 2.4 times the adopted value. Both rails and the coefficient are stored as reconfigurable parameters, so the release point is a configuration choice rather than a hardware limit.

Table 2. Manual-reference comparison for the $300 \times 50 \times 80$ cm treatment strip

Scenario	Severity class	SI (%)	Selected tank	Applied volume (mL)
S1	Mild	15	T1	180
S2	Moderate	35	T2	180
S3	Severe	80	T3	180

Hydraulic output was evaluated separately at the 560 mL upper command, as Table 3 presents. Collected volumes were 513 mL and 491 mL, shortfalls of 8.4% and 12.3%, and effective flow was 11.45 and 11.14 mL/s against the 12.5 and 12.7 mL/s calibration values used for those commands. This gap far exceeds the firmware's 1 ms timing resolution, so it is attributable to the open-loop hydraulic path and the collection method rather than to arithmetic error. Likely contributors are flow drift under sustained operation, residual liquid, and uncaptured mist. The two rows are sequential observations rather than replicated treatments, so the before and after cleaning labels are not evidence of a cleaning effect. Figure 9 presents the misting nozzle disassembled during that step. Delivery was collected from the full ten-nozzle boom into a graduated vessel, so the reported volume represents the whole array rather than a single nozzle; replication across the 180 to 560 mL range is required before the hydraulic loop can be characterised as reliable.

Table 3. Commanded and collected volume in two sequential hydraulic checks

Nozzle state	Commanded volume (mL)	Collected volume (mL)	Calibrated flow (mL/s)	Command duration (s)	Effective flow (mL/s)	Deviation (%)
Before cleaning	560	513	12.5	44.80	11.45	8.4
After cleaning	560	491	12.7	44.09	11.14	12.3



Figure 9. Misting nozzle disassembled for manual cleaning, showing the body, spring, check-valve poppet, and orifice cap.

Wireless signal strength declined from -80 dBm at 31 m to -91 dBm at 50 m while the station remained associated at every recorded point, and no association formed at 65 m, as Table 4 and Figure 10 present. Because most points carry a single reading and instantaneous values fluctuated by as much as 7 dB over tens of seconds, these measurements describe the tested path rather than a propagation model. One spray command was accepted when the dashboard displayed an RSSI near -88 dBm, which confirms delivery at that moment rather than a guaranteed control range, because the link could drop and reassociate near the far end. The local channel can therefore support station to UGV integration over tens of metres under the tested obstruction conditions. Packet delivery rate, round-trip latency, command loss, and reconnection time were not instrumented in this test, so these

observations characterise signal strength and association along a single obstructed route and should not be read as an operational range.

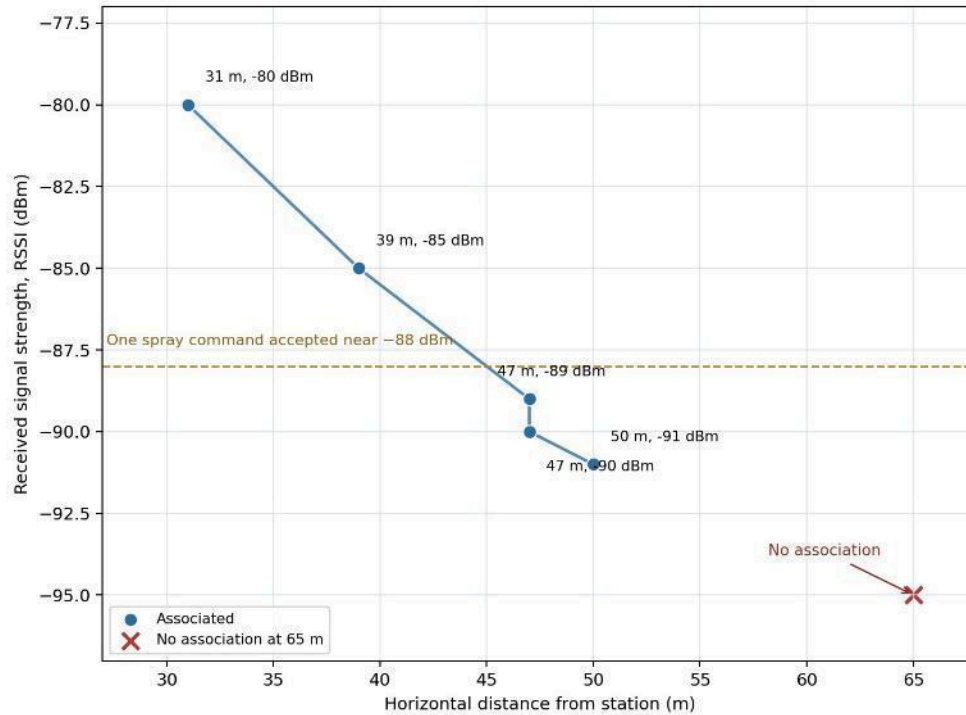


Figure 10. RSSI observations along the obstructed test path. The 65 m point had no association, and the dashed line marks the approximate RSSI at which one spray command was accepted.

Table 4. Distance, RSSI, and Wi-Fi association observed on the test path

Distance (m)	RSSI (dBm)	Association status
31	-80	Connected
39	-85	Connected
47	-89	Connected
47	-90	Connected
50	-91	Connected
65	Unavailable	Not associated

The station continued to broadcast status once per second while the pump was active, and the state machine returned to IDLE on both the stop command and the expiry of the calculated duration.

In the interface test, the dashboard emulated a live ANTRAC UGV and sent *updateLogic* payloads with index values of 15%, 35%, and 80%. The station selected T1, T2, and T3 in sequence, reported 180 mL and 14.29 s for each fixed-canopy case, energized the corresponding valve and pump, and returned to IDLE. The test exercised the command-to-actuation chain and verified compatibility with the intended message format, but not image acquisition, detection, index generation, navigation, or transmission from ANTRAC hardware. Because the ANTRAC UGV was not connected during this test, the result demonstrates message-format compatibility and station-side execution rather than live inter-device reliability.

d) Positioning, Limitations, and Further Work

The main outcome is an actuation-side architecture connectable to ANTRAC. Neural networks recognize chili disease symptoms from images (Kanaparthi & Ilango, 2026; Kim et al., 2025), while canopy sensing and flow modulation in variable-rate sprayers have been investigated separately (L. Li et al., 2018; Nan et al., 2023). This station connects the two by accepting a scalar condition input, exposing every arithmetic step, and converting the result into a selected liquid path and a finite pump command. Its isolated tank paths could support formulation rotation (Corkley et al., 2022), but that benefit remains architectural until products and schedules are evaluated. Ultrasonic

variable-rate sprayers have been validated in the field on apple (Salas, Salcedo, Garcia-Ruiz, & Gil, 2025), whereas the evidence reported here remains station-side.

Several design choices limit the present claim. Canopy dimensions are entered manually, the index selects only a tank rather than continuously scaling the dose, and the 180 mL lower rail dominated the reference cases, compressing the apparent dose range, so the term variable-rate is used here in the qualified sense of canopy-proportional dosing with severity-gated tank selection rather than continuous severity-based volume modulation. Hydraulic accuracy was measured only at the maximum command with two sequential collections, and wireless performance on a single obstructed route with sparse sampling. No bill of materials was documented, so low cost refers to commodity components rather than a demonstrated economic comparison of the kind reported for open-source agricultural platforms (de Moura Campos, de Oliveira, Mesquita, de Castro, & Ferrarezi, 2021). The station draws from a bench power supply during testing, and a solar charging station for electric farm machinery has been demonstrated as a renewable alternative for field deployment (Siskandar et al., 2024).

All tests used water on a bench or outdoor rig without living chili plants, formulated pesticide, or *Colletotrichum inoculum*, so the data do not establish deposition uniformity, biological control, crop safety, yield response, pesticide savings, or resistance management. Surfactants and suspended active ingredients alter viscosity, surface tension, droplet size, and nozzle behaviour, so field use requires recalibration with the intended formulation and an agronomically justified coefficient.

A live ANTRAC client should next log end-to-end messages, report packet delivery rate, latency, command loss, and reconnection time, and verify schema compliance. Hydraulic tests should span the 180 to 560 mL range with replication to report mean, spread, and percentage error, and measure nozzle distribution with water-sensitive paper against air-assisted references (Qiu et al., 2022). Field trials should compare the integrated system with uniform spraying on bearing chili plants, reporting incidence and severity separately alongside formulation use, deposition, crop injury, and yield. The boom should also be raised to remove the coverage shortfall before an endurance test of the pump, valves, and controller.

CONCLUSION

This research developed and functionally tested a pesticide spraying station as the actuation endpoint for the ANTRAC UGV. The contribution is an auditable path from a scalar disease index to a finite pump command, comprising the WebSocket interface, the ESP32 firmware, the canopy-to-dose calculation with its safety rails, three-tank selection, hydraulic execution hardware, and local status display. Every arithmetic step is printed in the paper, so a reader can reproduce the commanded volume from the configured canopy without access to the firmware. The verification also separates two error sources cleanly. Computation reproduced the manual reference exactly, whereas delivered volume fell short of commanded volume, which places closed-loop flow feedback ahead of dose-model refinement as the next station-side priority. Because the dashboard emulated ANTRAC and all spraying used water, the evidence covers station-side readiness only, and live integration with the UGV followed by field validation remains the next requirement. This study therefore reports a developed station subsystem and its interface rather than a fully integrated ANTRAC system.

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