Design and Analytical Verification of an Internet of Things Based Drip Fertigation System

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Abstract—This engineering design study specifies an Internet of Things based liquid fertilizer application system that separates soil-moisture irrigation demand from authorization to deliver fertilizer. An ESP32 controller coordinates water-level and flow interlocks, calibrated stock dosing, prewetting and line flushing, while retaining local control during loss of Wi-Fi. A deterministic reference model was executed with synthetic, already qualified sensor inputs at one-second intervals. For an illustrative 24-emitter arrangement, the assumed carrier flow is 0.80 L/min. A 60 mL stock dose at 30 mL/min requires 120 s; 60 s of prewetting and 90 s of flushing give a 270 s cycle, 3.60 L of carrier water and 3.66 L of total solution. All 12 predefined scenarios matched their expected outcomes, and 1,080 single-fault timing cases produced no violations of the specified dosing and shutdown invariants. A ±10% change in dosing-pump flow changes the delivered dose to 54–66 mL, demonstrating the limitation of timed open-loop metering. These results establish internal consistency of the stated design model. They do not demonstrate prototype performance, crop response or resource savings; physical calibration and field evaluation remain necessary.

Keywords—Internet of Things, drip fertigation, ESP32, soil moisture, dosing control, fault interlocks.

I. INTRODUCTION

Irrigation and nutrient application are related operations with different decision requirements. Irrigation responds to water availability in the root zone, whereas a fertilizer dose depends on the crop, growth stage, stock concentration and nutrient plan. Soil-water availability also depends on rooting depth and the difference between field capacity and wilting point; consequently, one moisture threshold cannot be transferred unchanged between crops and soils [1]. Fertigation introduces dissolved fertilizer into an irrigation stream and provides a practical route for coordinating these operations [2].

A manual arrangement depends on an operator to inspect the crop, open valves, prepare stock solution and stop injection. A timer can repeat an operating period but cannot establish whether water is actually flowing or whether fertilizer has already been delivered. Published sensor-controlled irrigation and Internet of Things (IoT) systems demonstrate that local measurements and remote access can support irrigation management [3], [4]. ESP32-based fertigation has also been demonstrated with electrical conductivity (EC) monitoring and a crop testbed [5].

A specific control error arises when a low soil-moisture signal starts both the water pump and fertilizer pump every time the soil appears dry. Sensor noise, a slow wetting response or repeated remote messages can then trigger several fertilizer applications for one intended dose. The present design treats water demand and fertilizer authorization separately. Water-only irrigation remains possible when no nutrient application is due, and a consumed fertilizer authorization cannot be replayed automatically.

The objective is to develop a transparent design for a small educational drip-fertigation installation at Government Polytechnic Karad. Its contributions are an explicit sequence of operating states, a bounded fertilizer authorization,

calculated water and stock volumes, and reproducible checks of abnormal operating conditions. The design connects sensing and electrical actuation with hydraulic delivery.

This engineering design case study evaluates a reference controller and a worked hydraulic arrangement using analytical and computational methods. It uses no prototype or crop measurements. Hardware elements are proposed requirements, and numerical examples are identified as assumptions or reference-model outputs. Physical calibration and matched field evaluation are required to establish resource consumption, crop response and deployment performance.

II. LITERATURE REVIEW

Gutiérrez et al. [3] combined root-zone measurements, a microcontroller gateway, actuator control and cellular communication in an automated irrigation system evaluated in a crop field. This work supports the separation of local decision making from remote observation. Its field outcome depends on its crop, comparator and experimental conditions, so its resource-saving figures cannot be adopted as expected performance for the present design.

Vinod Kumar S et al. [4] developed and tested an IoT drip-irrigation system for brinjal in vertisol-filled planter beds. They used distinct lower and upper moisture thresholds and compared the installation with an evapotranspiration-based treatment. The important methodological lesson is the use of a defined comparator and actual crop observations. Their numerical thresholds represent their soil and calibration conditions and are not assigned to the relative sensor index used here.

Idris et al. [5] reported an ESP32 fertigation system with electrical-conductivity feedback, remote monitoring and an eggplant testbed. That study controls the fertilizer mixture as well as its delivery. In contrast, the present baseline meters a previously prepared stock solution by time and assumes its concentration is known. It therefore does not claim closed-loop nutrient-concentration regulation or measurement of individual nitrogen, phosphorus or potassium availability.

Sensor calibration is an equally important part of the evidence chain. Nagahage et al. [6] compared a low-cost capacitive sensor with gravimetric measurements and a reference instrument, while Adla et al. [7] examined low-cost sensors across soil, temperature and salinity conditions. These studies show why a voltage-to-percentage display is insufficient evidence of volumetric water content. The present controller uses a relative index until a soil-specific calibration is available.

Kunt [8] describes an ESP32 irrigation concept combining monitoring and artificial-intelligence prediction. That work is a preprint and is treated as supporting design context rather than as independently confirmed agronomic evidence. The present study uses deterministic rules with stated timing and fault priorities. It does not require a prediction model or claim that predictive irrigation has been implemented.

TABLE I. SELECTED EVIDENCE AND RELEVANCE

Source	Evidence reported	Relevance here
Gutiérrez et al. [3]	Sensor-controlled irrigation with field evaluation	Local sensing and remote access
Vinod Kumar S et al. [4]	Drip irrigation with crop comparison	Separate start and stop thresholds
Idris et al. [5]	ESP32 fertigation with EC monitoring	Distinguish volume from concentration
Nagahage et al. [6]; Adla et al. [7]	Sensor calibration and characterization	Avoid uncalibrated moisture claims
Present study	Analytical sizing and synthetic controller traces	Bounded dosing and fault sequencing

The contribution is thus a documented control design and its bounded verification, rather than a claim to introduce IoT fertigation for the first time. The literature comparison also identifies the next evidence required: physical dosing calibration, hydraulic distribution measurements and a crop-specific trial.

III. METHODOLOGY

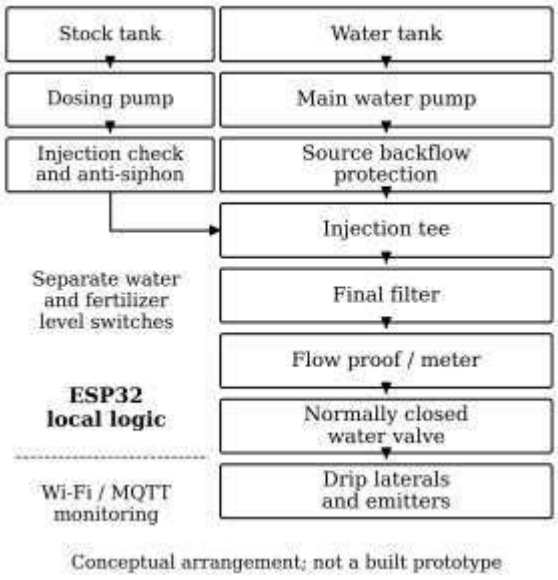


Fig. 1. Proposed hydraulic arrangement and local control boundary.

A. System boundary and architecture

The proposed installation contains a water tank, stock-solution tank, main water pump, dosing pump, normally closed water valve, final filter and drip laterals. Separate level switches monitor the two tanks. A soil-moisture sensor provides the irrigation-demand input; a DHT11 sensor provides contextual ambient temperature and relative humidity. A flow-proof device is added downstream of the injection assembly because a pump command alone cannot confirm water delivery. The conceptual arrangement is shown in Fig. 1.

Source backflow protection and an injection check or anti-siphon arrangement separate the supply and fertilizer paths. Injection is placed upstream of a final filter, with sufficient mixing distance before the emitters. These are design requirements, not a certified plumbing installation. The dosing pump must deliver against the actual line pressure, and its wetted materials must be compatible with the selected solution. Component models and pressure ratings must be selected during prototype construction.

B. Sensing and electrical interface

The ESP32 is selected for its general-purpose input/output, analogue acquisition and Wi-Fi capability [9]. An analogue-to-digital converter (ADC) channel on ADC1 is preferred for moisture sensing because ADC2 is shared with Wi-Fi on the classic ESP32 [10]. Input conditioning must keep sensor signals within board and converter limits. Espressif documents chip-to-chip reference variation and a calibration driver; electrical conversion calibration and soil calibration address different error sources and both are required [11].

The proposed signal path rejects acquisition errors, checks freshness and applies a five-sample median before threshold comparison. A three-second freshness limit and a one-second control interval are design settings. DHT11 observations may be logged every ten seconds; they do not independently trigger irrigation or determine fertilizer quantity. The reference-model tests start after input qualification, so median-filter delay, analogue noise and sensor ageing are not simulated.

Power stages must be selected from measured load current, starting current and supply voltage. The controller must not energize a pump directly from an input/output pin. Suitable relay or transistor drivers, fuses and suppression for inductive direct-current (DC) loads are required. Output pull-downs and de-energized valve closure reduce unintended startup actuation. A regulated low-voltage control supply, protected enclosure and separation of wet hydraulic parts from electrical connections are construction requirements.

C. Communication and command handling

The proposed communication stack is Wi-Fi with Message Queuing Telemetry Transport (MQTT) version 3.1.1 and a broker-connected dashboard. MQTT provides publish/subscribe messaging and delivery-quality levels; at-least-once delivery can include duplicate messages [12]. Therefore, application-level commands require a unique authorization identifier, an expiry time and a volume limit. Command topics must not replay retained dosing instructions. Telemetry may be retained when its timestamp is displayed, and the broker connection should use authenticated, encrypted transport.

Network messages request actions; they cannot override local water, flow, sensor or runtime interlocks. Loss of connectivity disables new remote instructions but does not cancel a valid local cycle. Consumed authorization identifiers are to be stored before energizing the dosing output. After a power interruption, the installation returns to an unarmed, de-energized state and requires local inspection and rearming. The computational reset case represents this policy; it does not test flash persistence or a real network stack.

D. Moisture and dosing calibration

For a sensor whose raw reading decreases as wetness increases, let x be the qualified reading and let xd and xw be dry and wet calibration endpoints. A relative index M is defined by Eq. (1), with clipping to the interval 0–100. This index is dimensionless. It must not be labelled volumetric water content without comparison against a physical reference. A reversed-output sensor requires the corresponding mapping.

$$M = \min(100, \max(0, 100\ \frac{x_d - x}{x_d - x_w})) \quad (1)$$

The illustrative start and stop indices are 35 and 55, respectively. They demonstrate hysteresis and are not recommended crop thresholds. Before field use, multiple soil samples should be compared with gravimetric measurements across the working moisture range. Calibration must account for installation depth and representative root-zone placement; one probe cannot establish moisture conditions across a heterogeneous field.

If the authorized nutrient mass is mn and the stock contains cs units of that nutrient per unit volume, the stock volume Vs follows Eq. (2). A stock concentration in mg/mL and nutrient mass in mg give Vs in mL. For a dosing-pump flow qd in mL/min, Eq. (3) gives the operating time td in seconds. The worked case starts with an assumed 60 mL stock-volume authorization; no crop nutrient mass is prescribed.

$$V_s = \frac{m_n}{c_s} \quad (2)$$

$$t_d = \frac{60\ V_s}{q_d} \quad (3)$$

Dosing calibration must collect and weigh or measure the delivered solution at the intended line pressure, supply voltage and tubing condition. At least three repeat collections at each selected operating point are proposed to separate repeatability from systematic error. A free-discharge measurement cannot establish flow against backpressure. The current reference model assumes constant flow and consequently cannot verify pump accuracy.

E. Hydraulic sizing and flushing assumptions

For N emitters, each nominally discharging qe L/h, carrier flow Qw in L/min follows Eq. (4). Table II defines the illustrative test arrangement. Equal emitter flow, primed lines, unchanged initial and final hold-up, negligible leakage, adequate pressure and immediate establishment of nominal flow are analytical assumptions. Pipe friction, elevation and pressure-dependent emitter behaviour are outside this calculation.

$$Q_w = \frac{N\ q_e}{60} \quad (4)$$

TABLE II. ASSUMPTIONS FOR THE WORKED DESIGN CASE

Parameter	Assigned value
Emitters N and nominal emitter flow	24; 2 L/h each
Nominal carrier flow Qw	0.80 L/min
Authorized stock volume Vs	60 mL
Assumed dosing flow qd	30 mL/min
Prewetting and dosing times	60 s; 120 s
Assumed downstream hold-up VL	0.40 L
Flush factor f and flushing time	3 volumes; 90 s
Maximum active cycle; flow grace	360 s; 5 s
Dry and wet index thresholds	35; 55
Controller interval; restart delay	1 s; 30 s

A provisional flushing duration tf is calculated from downstream hold-up VL, carrier flow and a selected volume factor f using Eq. (5). Final flushing must be established from the actual layout and distal-line observations. Micro-irrigation maintenance guidance identifies filtration, backflow prevention and removal of fertilizer from laterals as necessary operational considerations [13]. The factor of three in this example is a calculation assumption, not a universal recommendation.

$$t_f = \frac{60\ f\ V_L}{Q_w} \quad (5)$$

For comparison, an ideal well-mixed hold-up volume predicts a remaining concentration fraction R after f volume exchanges according to Eq. (6). This deliberately simplified washout model illustrates why a calculated flush duration does not prove complete removal. Actual pipe transport includes displacement, dispersion, dead volumes and unequal lateral residence times.

$$R = \frac{C}{C_0} = \exp(-f) \quad (6)$$

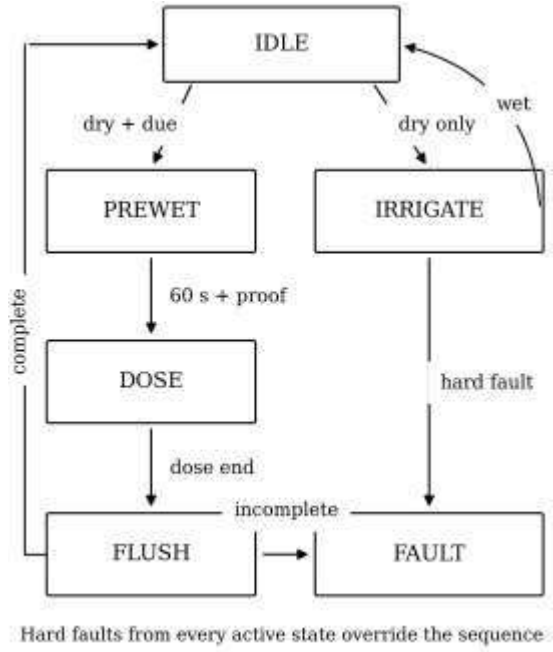


Fig. 2. Principal state transitions; hard faults have highest priority.

F. Local control sequence and interlocks

The reference controller has six states: IDLE, PREWET, DOSE, FLUSH, IRRIGATE and FAULT (Fig. 2). In IDLE, dry soil can start a cycle only after valid inputs and adequate water are confirmed. An unused, valid fertilizer authorization and adequate stock select PREWET; otherwise the controller selects water-only IRRIGATE. The authorization is reserved immediately before the first dosing output. A minimum restart delay limits immediate cycling after a normal stop.

PREWET operates the water path for 60 s. Dosing starts only with proven flow and an available authorization. DOSE then runs for at most 120 qualified one-second intervals. On dose completion, FLUSH supplies plain water for 90 s before normal shutdown. Water-only IRRIGATE ends at the upper moisture threshold or the runtime limit. A wet condition during PREWET stops the cycle before any fertilizer is admitted.

Priorities are evaluated before each output update. Invalid or stale moisture input, low water, controller reset, the active-cycle runtime limit, or loss of proven flow after the five-second startup grace cause immediate modeled transition to FAULT. All outputs are OFF in FAULT. When fertilizer becomes low or the upper moisture threshold is reached during an incomplete dose, injection stops first and water-only flushing continues if the water path remains healthy. The sequence then latches an incomplete-dose fault for acknowledgement. A hard fault during flushing still overrides the flushing request.

This distinction prevents an unconditional flush from operating a dry pump. An interrupted authorization remains consumed; an operator must reconcile the partial quantity before approving another dose. The controller also checks that the configured prewetting, dosing and flushing times fit within the active-cycle limit. Persistent storage integrity, relay welding and valve leakage require separate physical safeguards and are not covered by the state logic alone.

G. Computational verification protocol

A Python 3.12.14 reference model was executed with a fixed step of one second. At tick t, inputs and events are evaluated first, transitions occur next, and outputs apply over the interval from t to t + 1 s. The initial condition is an armed IDLE controller with valid configuration and one unused fertilizer authorization, represented by a Boolean consumption flag. Identifier parsing and expiry checks belong to the proposed communication layer. Normal synthetic moisture is 30 until t = 270 s and 60 thereafter. Water level, stock level, flow proof and sensor validity are initially true. Soil-water balance, crop growth, actuator dynamics and packet transport are excluded.

Twelve predefined traces test nominal operation, wet soil, absent water, absent flow, loss of flow at 90 s, low fertilizer at 90 s, a wet signal at 120 s, Wi-Fi loss from 90 to 239 s, invalid moisture at 90 s, water-only runtime termination, repeat authorization and reset at 90 s. The repeat-authorization trace adds a second dry interval from 300 to 479 s while reusing the consumed identifier. All traces run for 400 s except this two-cycle trace, which runs for 520 s.

An additional deterministic sweep applies one persistent fault at each integer time from 0 through 269 s. The four fault types are low water, absent flow, invalid moisture and low fertilizer, producing 4 × 270 = 1,080 traces and 432,000 one-second updates. At every update, assertions check that dosing implies pump and valve commands plus valid water, stock, flow and moisture conditions; cumulative dosing time does not exceed 120 s; FAULT outputs are OFF; and an active cycle remains below 360 s. This is a defined single-fault sweep, not exhaustive verification of all inputs or hardware failures.

H. Physical evaluation required after construction

A future bench study should independently measure dosing volume, water flow, startup response and shutdown delay. At least 24 emitter collections should cover near, middle and distal positions rather than only the easiest access points. Low-quarter distribution uniformity can be calculated using Eq. (7), where the numerator is the mean flow of the lowest-flow quarter and the denominator is the mean of all measured flows [14]. This metric is not computed here because no emitter measurements are available.

$$DU_{lq} = 100 \frac{\bar{q}_{lq}}{\bar{q}_{all}} \quad (7)$$

A matched field comparison should hold crop, treated area, growth stage and target nutrient mass comparable, while recording irrigation volume, fertilizer mass, rainfall, labour and crop response over a stated period. Repeated observations and uncertainty reporting are needed before calculating savings or testing treatment differences. A single successful switching demonstration would establish operation, but would not establish agronomic benefit.

IV. RESULTS

A. Calculated nominal operating cycle

The analytical carrier flow is 24 × 2/60 = 0.80 L/min. At the assumed stock flow of 30 mL/min, a 60 mL authorization requires 120 s. The assumed 0.40 L hold-up and three-volume flush require 1.20 L of carrier water, corresponding to 90 s. Therefore, 60 s of prewetting, 120 s of dosing and 90 s of flushing occupy 270 s, leaving 90 s below the 360 s active-cycle limit.

Carrier-water volumes are 0.80 L during prewetting, 1.60 L during dosing and 1.20 L during flushing, for a total of 3.60 L. Adding the 0.060 L stock volume gives 3.66 L of total emitted solution under the equal-flow, zero-leakage assumptions. The stock fraction is 3.61% during injection and 1.64% over the complete event. These fractions describe stock solution, not nutrient concentration; nutrient mass still depends on the stock composition.

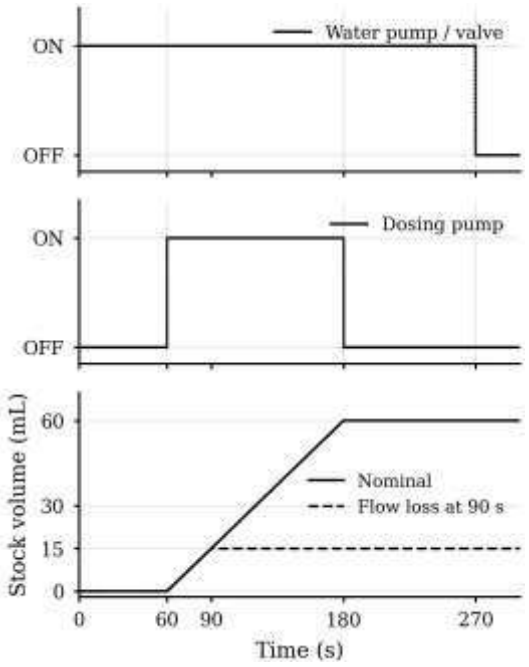


Fig. 3. Synthetic nominal outputs and cumulative dose with a flow fault.

B. Predefined scenario outcomes

All 12 scenarios matched the expected state and volume outcomes. Table III reports carrier water at the assumed flow, stock dose and the final pump stop time. In S4, the pump is commanded during the five-second proof grace but zero carrier volume is credited because flow is absent. Stop time is measured from the beginning of the trace; it is not cumulative pump runtime for the two-cycle case S11.

TABLE III. REFERENCE-MODEL SCENARIO RESULTS

Case and condition	Water (L)	Stock (mL)	Stop (s)
S1 Nominal fertigation	3.60	60	270
S2 Initially wet soil	0.00	0	0
S3 Low water at start	0.00	0	0
S4 No flow at start	0.00	0	5
S5 Flow loss at 90 s	1.20	15	90
S6 Low stock at 90 s	2.40	15	180
S7 Wet signal at 120 s	2.80	30	210
S8 Wi-Fi interruption	3.60	60	270
S9 Invalid sensor at 90 s	1.20	15	90
S10 Water-only timeout	4.80	0	360
S11 Same token, two cycles	6.00	60	480
S12 Reset at 90 s	1.20	15	90

Flow loss at 90 s stops dosing after 30 s of injection, giving a modeled partial stock dose of

15 mL. Low stock at the same instant also limits the dose to 15 mL, but permits 90 s of flushing and ends at 180 s. Reaching the wet threshold at 120 s limits stock to 30 mL and ends flushing at 210 s. These incomplete-dose cases require acknowledgement; they do not trigger automatic replacement dosing.

The Wi-Fi interruption case reproduces the nominal 60 mL dose and 270 s stop time because network availability is not a local hydraulic permission. In S11, a second irrigation demand receives water only: total carrier water is 6.00 L across the two cycles while total stock remains 60 mL. Thus the consumed token prevents a second fertilizer application despite continued presentation of the same authorization.

C. Fault timing and operating bounds

The 1,080 single-fault timing traces produced zero violations of the four assertion groups across 432,000 updates. No trace exceeded 60 mL of modeled stock delivery. The runtime case stopped water-only irrigation at 360 s, and reset caused the FAULT state without an automatic restart. Faults occurring on the modeled one-second boundaries are processed before that interval's outputs. An asynchronous physical fault can arrive between samples and has additional sensor and actuator delay; the sweep does not measure or bound those hardware delays.

D. Dosing sensitivity and flushing residual

Table IV holds the 120 s dosing command constant while varying actual pump flow by ±5% and ±10%. The resulting delivery range is 54–66 mL. This is a sensitivity calculation, not an observed calibration curve. At 30 mL/min, an additional one-second actuation error corresponds to 0.5 mL. If a +10% flow error and one additional second occur together, the calculated upper dose is 66.55 mL. Digital timing precision therefore cannot substitute for flow calibration.

TABLE IV. CALCULATED SENSITIVITY AT A FIXED 120 S COMMAND

Assumed flow (mL/min)	Delivered stock (mL)	Error from 60 mL
27	54	-10%
28.5	57	-5%
30	60	+0%
31.5	63	+5%
33	66	+10%

For f = 3, the ideal mixed-volume washout result is exp(−3) = 0.0498, or 4.98% of the concentration at the start of flushing. This is not the percentage of the injected nutrient dose remaining. Even this simplified model predicts nonzero residue. The computed 90 s is provisional; the actual duration must be established from distal outlets and acceptable residual concentration, with flush water included in the irrigation budget.

V. DISCUSSION

A. Interpretation of the design evidence

The nominal arithmetic, expected trace outcomes and fault sweep are mutually consistent under the stated assumptions. The most useful design result is that irrigation demand need not imply nutrient demand. The authorization rule preserves a 60 mL stock limit across two water-demand cycles, while flow proof prevents injection into a non-flowing carrier path. These are control properties of the reference model, not evidence of improved crop nutrition or lower consumption in a field.

The sweep provides repeatable coverage of single persistent faults at specified times. It does not cover simultaneous faults, intermittent contacts, noisy analogue signals, corrupted configuration, clock drift, stuck sensor readings within the valid range, or a pump that continues operating after its command is removed. Such faults require targeted hardware testing and, where appropriate, independent cutoff mechanisms. The model should therefore guide prototype tests rather than replace them.

B. Agronomic and hydraulic limits

A relative moisture index cannot be interpreted as a crop water balance without a physical calibration. Wetting-front travel can also delay the root-zone response after water is applied. The selected 35/55 thresholds, 60 mL dose and 270 s sequence serve to exercise the controller; they are not a fertilizer recommendation for any crop. Stock composition, irrigation-water chemistry, soil texture and crop stage must be established before a field treatment is selected.

A completed injection command does not establish uniform fertilizer delivery. Pump flow can vary with backpressure, tubing wear and voltage, while lateral pressure and clogging can create unequal emitter discharge. The proposed final filter, check arrangements and flush phase address identifiable design needs, but their effectiveness remains to be measured. Electrical conductivity can support mixture monitoring in an

extended system, although it does not directly identify the concentration of each nutrient.

C. Deployment implications and next development step

The electrical design should use predictable de-energized behaviour and a local control loop that remains operational without an internet connection. Valve travel and pressure transients are omitted from the model; a physical implementation must verify valve opening before pump startup and pump shutdown before valve closure. Remote commands also require freshness checks, persistent token storage and acknowledgement. The model represents the intended policy without proving the electrical or communication implementation.

A system price or payback period requires procurement, energy, maintenance and labour data, which are outside this design study. A future cost assessment should include sensors, hydraulic fittings, protective electrical hardware, enclosure, communication and replacement pump tubing. The cost boundary must therefore cover the complete installation.

The next development step is a bench prototype with independently measured carrier flow and stock volume under real backpressure. After electrical and hydraulic testing, a crop-specific pilot can establish threshold suitability, distribution uniformity and agronomic outcomes. Higher-level weather integration, additional zones and solar supply can then be considered using measured requirements rather than assumed savings.

VI. CONCLUSION

An ESP32-based IoT drip-fertigation design has been specified with separate irrigation demand, bounded stock authorization, flow and level interlocks, prewetting, timed injection and flushing. For an illustrative 24-emitter case, analytical sizing gives a 120 s stock injection and 270 s complete cycle, with 3.60 L of carrier water and 60 mL of stock. Twelve predefined computational scenarios matched their expected results, and 1,080 single-fault timing traces produced no violations of the stated model assertions.

The sensitivity calculation shows that ±10% pump-flow variation changes the timed dose to 54–66 mL, while the mixed-volume flushing model retains a nonzero residual after three volume exchanges. These findings make calibration and outlet verification necessary parts of the proposed implementation. The study establishes a reproducible basis for prototype development; it does not demonstrate experimental dosing accuracy, water or fertilizer savings, crop yield improvement, or field reliability.

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DATA AND COMPUTATIONAL SCOPE

The numerical assumptions and computational protocol are stated in Sections III and IV. The accompanying computational supplement contains the executable reference model, synthetic traces, result summary and figure-generation code. Diagrams are original conceptual drawings; plotted traces are reference-model outputs.

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