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Pid-Controlled Irrigation and Nutrient Scheduling for Improved Crop Resource Efficiency: A Matlab/Simulink Simulation Study

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Abstract
Precision agriculture requires timely and accurate control of irrigation and nutrient delivery, yet many smallholder systems remain dependent on fixed schedules that disregard real-time soil variability. This paper presents a simulation-based design and evaluation of an integrated proportional-integral-derivative (PID) control strategy for closed-loop irrigation and fertigation management, with crop-specific adaptation for maize, tomato, and okra. A MATLAB/Simulink environment is used to model soil water and nutrient dynamics using transfer-function representations and disturbance inputs representing rainfall and weather variability. The controller is tuned iteratively through closed-loop step-response analysis using standard time-domain metrics, namely peak overshoot, settling time, and steady-state error, with anti-windup constraints to prevent actuator saturation. Results show stable convergence to a 5 %t soil moisture reference, with low overshoot of 5 % for maize, 4 % for tomato, and 6 % for okra, and settling times of 2.1 days, 1.8 days, and 2.4 days, respectively. Steady-state tracking errors remain below 3 % across crops, confirming robust long-term regulation. Compared with open-loop scheduling, the PID strategy yields substantive input efficiencies, achieving 24 to 33 % reductions in irrigation water and 17 to 26 % reductions in fertiliser use, while improving simulated yield performance by 12 to 18 % in maize, 15 to 20 % in tomato, and 10 to 15 % in okra. These findings indicate that classical feedback control, when properly tuned and structured for agronomic constraints, can deliver practical and measurable resource savings and support sustainable intensification in data-constrained farming contexts.

Keywords: *precision agriculture, PID control, irrigation scheduling, fertigation, MATLAB/Simulink, soil moisture regulation, resource optimization*

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I. INTRODUCTION

Sustainable crop production requires effective management of water and nutrients, most especially in sub-Saharan Africa, where the unpredictable rainfall and the increased input demands severely limit crop productivity [3][16]. Conventional irrigation is a technology that depends on a fixed timetable where irrigation systems do not respond to the reaction of the soil, leading to wastewater, erosion, and loss of yield in Nigeria [4][5]. These open-loop systems do not react to variability of rainfalls or variable evapotranspiration, which means that crops are exposed to moisture-related stresses or waterlogging at sensitive development stages [6].

The limitations are overcome by precision agriculture that provides sensing, computation, and automated actuation, which facilitate the delivery of needs-based inputs [5]. Practical feedback control systems, especially proportional-integral-derivative (PID) controllers, provide effective control of soil moisture and nutrient status by producing corrective, proportional to their present error, past cumulative error, and future projected error behaviour [1][2]. This arrangement provides quick disturbance suppression together with stationary long-term monitoring and is yet computationally efficient and understandable; the latter aspect is very important to resource-limited dynamic smallholder habitats [1][13].

Recent research shows huge efficiency improvement by sensor control automation. IoT-based smart irrigation solutions save 20-35% of water [9], whereas PID-based fertigation saves 15-25% of nutrients than batch-mixing strategies [13]. Nonetheless, state-of-the-art machine learning algorithms can usually be scaled to be very large, and necessitate large-scale data sets and facilities, which are beyond the scope of agricultural systems development [6][16]. Classical PID control provides a more pragmatic option as it provides real improvements that can be measured with maintainable algorithms that can be performed in a stable state when there is a lack of data [1][2].

Designing this kind of control requires adaptation of crops. Maize will have the highest water use and acute stress sensitivity at tasseling, tomato is sensitive to a lack of moisture, which can also be deadly to blossom, and tomatoes should be watered regularly in the stages of pod formation [7][12][15]. Although this is variable, there still exists a lack of unified simulation-based frameworks that can simultaneously control irrigation and nutrient delivery amongst a variety of crops [18][19].

The paper formulates and analyses a combined PID-controlled irrigation and fertigation framework of maize, tomato, and okra in MATLAB/Simulink. The contribution is three times.

i. Interlocked water-nutrient management with decentralised PI.
ii. Parameterisation by crops according to evolutionary differences in physiology; and
iii. Strict validation with the help of stability measures and comparison of efficiency with fixed-schedule baselines.

II. RELATED WORKS

2.1. Smart irrigation and sensor-guided automation

Recent reviews show that smart irrigation systems are often integrated with soil moisture sensors, evapotranspiration-based demand forecasting, and automated valves/pumps to generate more precise root-zone water content controls as compared to manual or timer-based systems [5].

According to the literature published in the world and the continents, sensor-based irrigation mitigates the variation in moisture, enhances water productivity, and allows crops to exhibit consistent performance since moisture content in the soil remains within specific ranges despite changes in atmospheric demand [5].

IoT-based irrigation architectures are also enhanced and practical in the sense that they support remote monitoring, handling alarms, and near real-time actuation of irrigation systems, which lowers labour demands and enhances uniformity in the operation [9]. All of these results place sensor-guided automation as a base layer to any irrigation strategy that is closed loop.

2.2. Fertigation, nutrient dynamics, and the need for feedback regulation

In addition to water, the delivery of nutrients via fertigation is also becoming a problem of control since the nutrient loads are prone to drift due to the variability of plant uptake, transformation by microbes, and effects of dilution by irrigation or rainfall [6][7].

The research on fertigation in the global frontier has highlighted the fact that stability of nutrients in the root zone is challenging, as when batch mixing or fixed-dose application is used, and in a manner where low-level demand phases follow the primary growth phase. The research findings have pointed out that the stability of nutrients in the root zone is challenged [6].

This means that real-time correction systems that are capable of modulating dosing depending on observed or estimated nutrient-related parameters like EC, NPK sensors values or proxy variables are an increasing basis of nutrient-use efficiency and environmental protection. This puts fertigation a loyal partner to closed-loop irrigation, in which both loops have to align to stabilise the availability of moisture and nutrients as a resource-growth potential [7][13].

2.3. Control strategies in precision irrigation, PID and beyond

Several more sophisticated controllers have been explored in the area of irrigation and fertigation control, such as fuzzy logic controllers, optimisation-based controllers, and robust control policies that are adapted to uncertainty [8][10].

The most recent developments have also covered fuzzy PID methods and optimisation-aided tuning, which provides increased flexibility in cases where the dynamics of the plants are non-linear or time-varying [10]. Nonetheless, pragmatic trade-off in the literature also underlines the fact that the ability to turn up controllers can decrease with the depth of sophistication in scenarios with resource constraints as a result of the computational load, tuning requirements, busy-work legitimate of verification, and an infrastructure requirement [1]. In the case of the agricultural environment, control methods should be robust, interpretable and lightweight, but should provide quantifiable control and enable increases in efficiency [1][2].

The proportional-integral-derivative control is most frequently found in this trade space as it is computationally cheap, predictable in its behaviour and can be tuned in a systematic manner using classical measures of performance, such as the overshoot, settling, and steady-state error [2]. The empirical evidence that has been documented in the studies around the world shows that PID-based irrigation can be superior to the threshold-based irrigation and the simple on/off irrigation system since it is known to smooth the variations of moisture and enhance disturbance recovery, particularly in the conditions of high evapotranspiration rates and and variable field environment [2]. There are also PID-controlled fertigation reports that have shown to be successful in stabilisation of nutrient supply, enhancing nutrient-use efficiency, and crop vigour due to constant availability of root-zone nutrients [13].

2.4. Simulation-based evaluation as a necessary bridge to deployment

The common gap found in the literature is that most of the literature introduces ideas of automation of irrigation without a demanding, crop-specific validation workflow to quantify the stability, transient response and efficiency trade-offs when subjected to disturbances. This application is largely accepted by simulation using MATLAB/Simulink since it enables application of controlled experiments, repeatable testing of the scenarios, and systematic controller tuning prior to field implementation [18]. Specifically, validation by simulation mitigates the risks and costs of trial-and-error hardware discovery, and allows the transparent assessment of the behaviour and control of variability of rainfall pulses and evapotranspiration [19]. This is ensuring that in addition to being a convenience, simulation is a facilitating tool to defensible control-system design in the agricultural arena [18][19].

2.5. Identified gap and motivation for this study

Although the current research demonstrates that there is a robust literature on smart irrigation and fertigation, a common finding in the literature is that there is no disseminated, simulation-validated, crop-specific framework of PID that can achieve control of irrigation water and nutrient delivery, and which can and surely provide a comparison of performance with conventional fixed-timetable operation using both control metrics and agronomic efficiency indicators. Other literature also puts relative emphasis on stability, responsiveness, and disturbance rejection as a formal validation criterion, though such properties are required in a plausible evaluation of closed-loop control [1][2][13].

The comparison of the multiple studies carried out on smart irrigation systems presented in Table 1 indicated differences in the control methods, water-nutrient integration, crop specificity, validation measure, and simulation application. It demonstrates that, although individual studies investigate fundamental control techniques such as PID, fuzzy PID, or sliding mode control, not all of them use a coupled water-nutrient control and are not multi-crop. Some of them are crop-specific or involve fertigation, but the metrics of evaluation are typically restricted to generic measurements like stability, robustness or yield. Compared to this, it offers a more holistic methodology through the combination of water and nutrient management, multi-crop (maize, tomato and okra) cultivation and uses complex performance metrics such as overshoot, settling time and steady-state error, and is validated using simulations to guarantee more reliable results.

Table 1: Comparison of Control Strategies in Smart Irrigation Systems

Study	Control Approach	Coupled Water–Nutrient	Crop-Specific	Validation Metrics	Simulation-Based
Dantas et al. [5]	Smart irrigation review	No	No	Water productivity	No
Liu et al. [10]	Fuzzy PID	Yes (fertigation)	No	Stability, efficiency	Yes
García et al. [8]	Sliding mode control	No	Yes (pecan)	Robustness	No (field)
Mendoza et al. [13]	PID	Yes	Yes (tomato)	Yield, efficiency	No (greenhouse)
Zhou et al. [18]	Simulation framework	No	No	Stability	Yes
This work	Classical PID	Yes	Yes (maize, tomato, okra)	Overshoot, settling time, steady-state error, efficiency	Yes

III. METHODOLOGY

3.1. Research Design and Data Sources

This research will take a quantitative, simulation-based experimental design that is based on control systems engineering. The problem of irrigation and scheduling of nutrients is stated as a closed loop control system whereby the soil moisture and nutrient contents are controlled to established crop-specific reference points. The whole system is done in MATLAB/Simulink (R2023b) with a model-based design approach which makes it possible to examine and analyse systematically, repeatably and verify performance before going to the field. Exogenous interruptions that reflect changes in rainfall and evapotranspiration (ET) are also added and are used to simulate natural environmental conditions, as well as test controller robustness.

3.2. System Architecture and PID Controller Design

The framework suggested combines irrigation and fertization as feedback fulfilled loops. Each crop (maize, tomato, and okra) has moisture and nutrient reference profiles, which are established using agronomic requirements and controller responds to the difference between setpoint and the value observed or estimated of the process variable. Simulink In Simulink, a subsystem of the plant occurs to balance soil water and nutrient within the root-zone soil and actuator blocks occur pages respectively, to represent irrigation flow and fertiliser dosing limits. Sensor blocks are used to offer the necessary real time correction feedback variables.

The hierarchical process flow of the proposed system is shown in this block diagram (Figure 1): crop-specific moisture and nutrient setpoints are calculated, compared with measured feedback to calculate errors, and fed to the decentralised irrigation and Nutrient PID controllers, which are translated into actuator commands that are used to control water flow and fertiliser rate to the Plant Subsystem that represents soil dynamics, and closed by continuous feedback control.

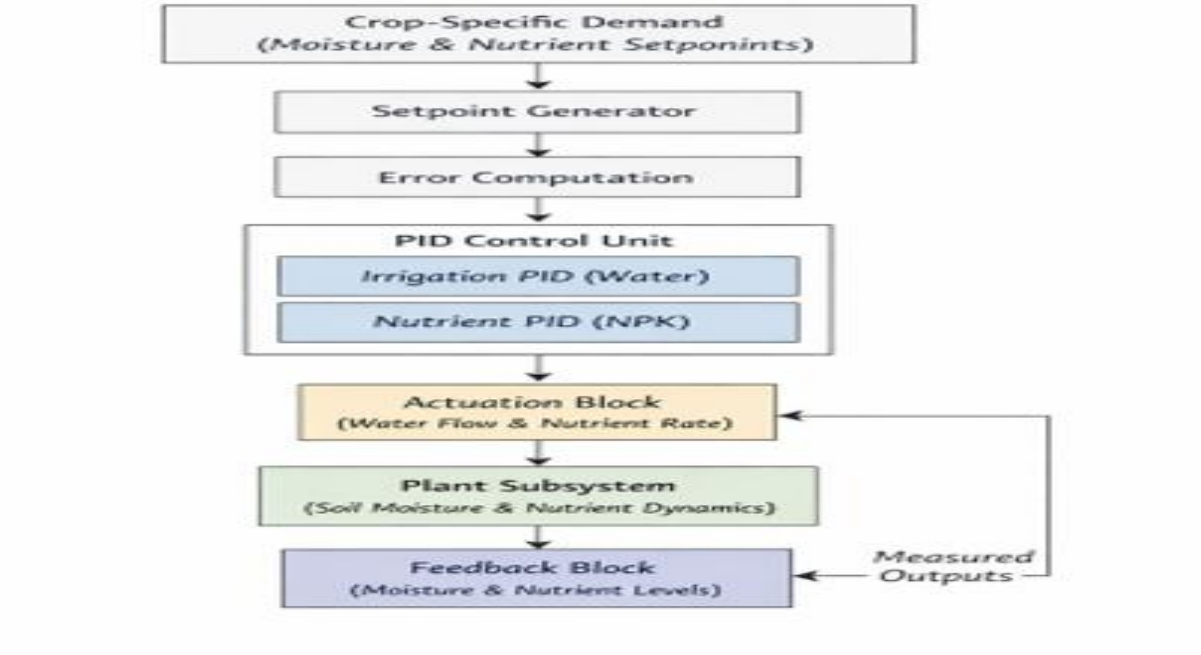

Figure 1: Design Architecture

Soil moisture dynamics:

$$\frac{d\theta(t)}{dt} = \frac{I(t)+R(t)-ET_C(t)-D(t)}{Z_r} \qquad (1)$$

where $\theta(t)$ is volumetric soil moisture content, $I(t)$ irrigation input, $R(t)$ is rainfall, $ETc(t)$ all, $D(t)$ is crop evapotranspiration, is drainage loss, and is effective root zone depth.

Nutrient concentration dynamics:

$$\frac{dN(t)}{dt} = F_n(t) - U_n(t) - L_n(t) \qquad (2)$$

where $N(t)$ is nutrient concentration, $Fn(t)$ is the fertiliser application rate, $Un(t)$ is plant nutrient uptake, and $Ln(t)$ is nutrient leaching loss.

Discrete-time PID control law:

$$u(k) = Kpe(k) + KiTs\sum j = 0ke(j) + Ts/Kd[e(k) - e(k-1) \qquad (3)$$

$e(k)=r(k)-y(k)$ = control error, T_S = sampling time (1 hour for irrigation, 1 day for nutrients)
K_p, K_i, K_d = proportional, integral, and derivative gains

3.3. MATLAB/Simulink Model Implementation

Specific Simulink subsystems were created that modelled maize, tomato and okra setpoints specific to crops and dynamic behaviour, and were combined to form a unified model to compare their behaviour under common disturbance conditions. The irrigation PID and nutrient dosing PID blocks, delay/transport elements, saturation constraints and output channels of key indicators, i.e. soil moisture, irrigation rate and fertiliser rate may be found within each crop module.

Figure 2 represents the PID control architecture of the irrigation and fertigation of okra which is decentralised. The system is constructed with three principal control loops with the irrigPID controlling water application through soil moisture error, FertPID controlling the application of fertiliser through nitrogen error, and finally ECPID/pHPID that measures the quality of nutrient solutions. The important inputs are rainin and petin, which are taken to signify rainfall and possible disturbances of evapotranspiration. Block atomically the 1/z blocks are used to execute on a discrete time and the saturation blocks (irrigsat, fertsat) place actuator control limits to avoid over- application. Feedback paths provide a possibility to have closed-loop correction on measured soil conditions. The design can be interpreted as drought-tolerant properties of okra by the conservative tuning parameters with less proportional and integral gains.

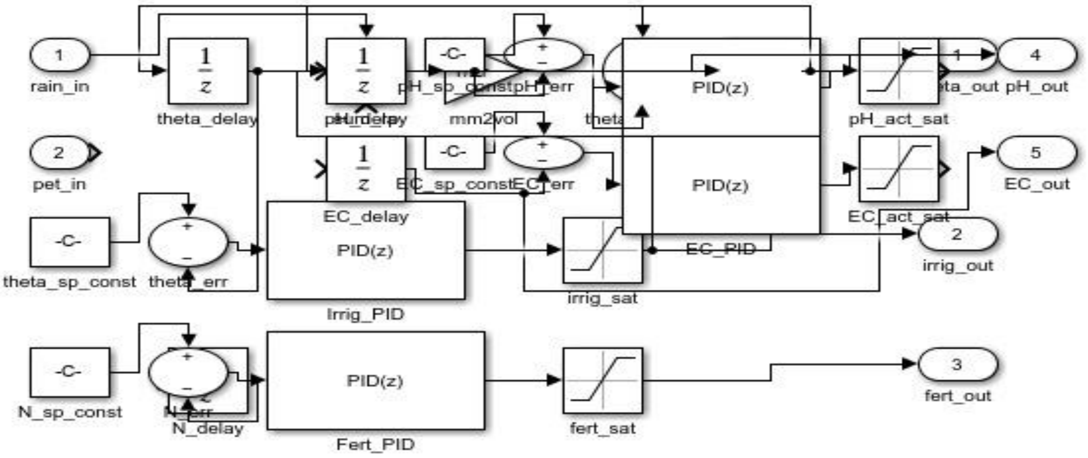

Figure 2: Individual PID control system module (crop-specific Simulink subsystem) – Okra.

Figure 3 introduces the maize-specific control module that has the same architectural design as okra, but this time it was aggressively tuned to the high-water requirement of maize. The Irrig_PID employs greater gains (K_p = 2.5, K_i = 0.8) to achieve high rates of response with a settling time of 2.1 days, compared to the okra of 2.4 days. At tasseling and silking periods of development, critical growth stage protection is of concern. Other significant contributions include the EC_delay block that considers nutrient transportation lag in the deep root system of maize, the mm2vol block that calculates volumetric moisture and the theta_delay block that compensates for the delay of soil moisture measurements. The increase in response speed helps in the stress avoidance of moisture to maize at its most sensitive reproductive stage.

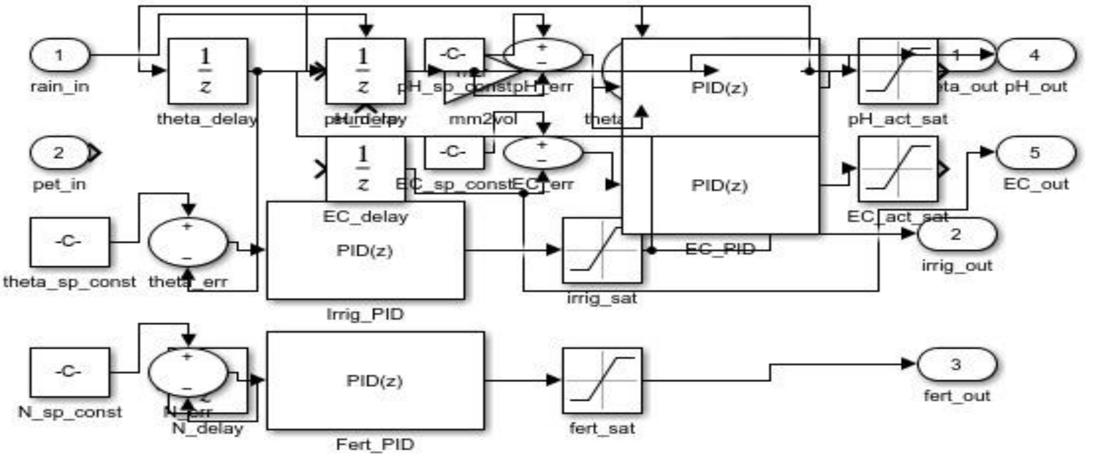

Figure 3: Individual PID control system module (crop-specific Simulink subsystem) – Maize.

Figure 4 represents the tomato control module, which has been optimised in order to maintain the moisture constant to avoid the occurrence of physiological disorders. It has the lowest control and the lowest settling time of one point eight days, and has an overshoot setting at 4 % that has the lowest among the three crops. The largest proportional gain (K_p=3.0) enables the correction of errors instantly, whereas the best elaborate derivative (K_d=0.4) absorbs the variation. Special focus on pH regulation will provide apples with calcium supply that is vital in fruit quality and prevention of blossom-end rot. This behaviour during the fruiting pattern is expressed by the aggressive tuning of tomatoes which is intolerant of fluctuations in moisture.

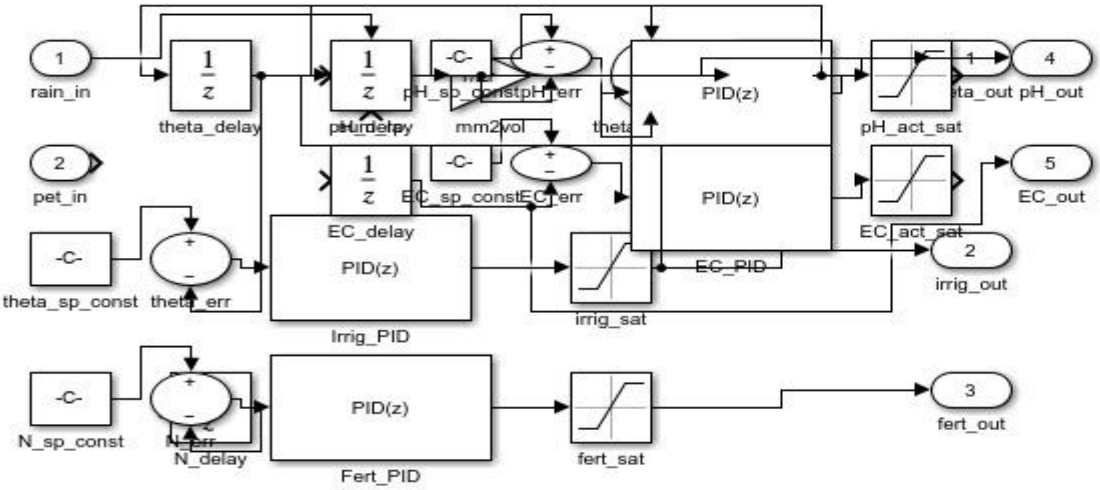

Figure 4: Individual PID control system for tomato

The three diagrams are likewise modular, allowing scaling and the use of a specific parameterisation, i.e. crop-specific, since okra is conducive to water-saving, maize to fast stress tolerance, and tomato to fluctuation avoidance.

This is an integrated simulation environment with three crop-specific PID control modules running under common environmental conditions as reflected in Figure 5. The model comprises three parallel subsystems that are vertically arranged (maize to okra) but stacked vertically. All the modules receive common disturbance inputs on the left: rain_sig feeds in common signals of the quantity of rainfall, pet_sig feeds in common signals of the quantity of evapotranspiration of the atmospheric water in a state of want. These common inputs allow considering the response of different tunings of controllers to the same environmental perturbation.

The subsystems have internal feedback of their own, but the subsystems have fabricated standardised output ports on the right-hand side, such as ferti_out (fertiliser rate), irrig_out (volume of water), theta_out (soil moisture), pH_out (acidity) and EC_out (electrical conductivity). There are two roles of this architecture: to prove that decentralised PID controllers can be used without interacting with one another in the outcome of some shared disturbances, and to allow resource efficiency and responsiveness of control with respect to various crops to be directly compared in the same circumstances.

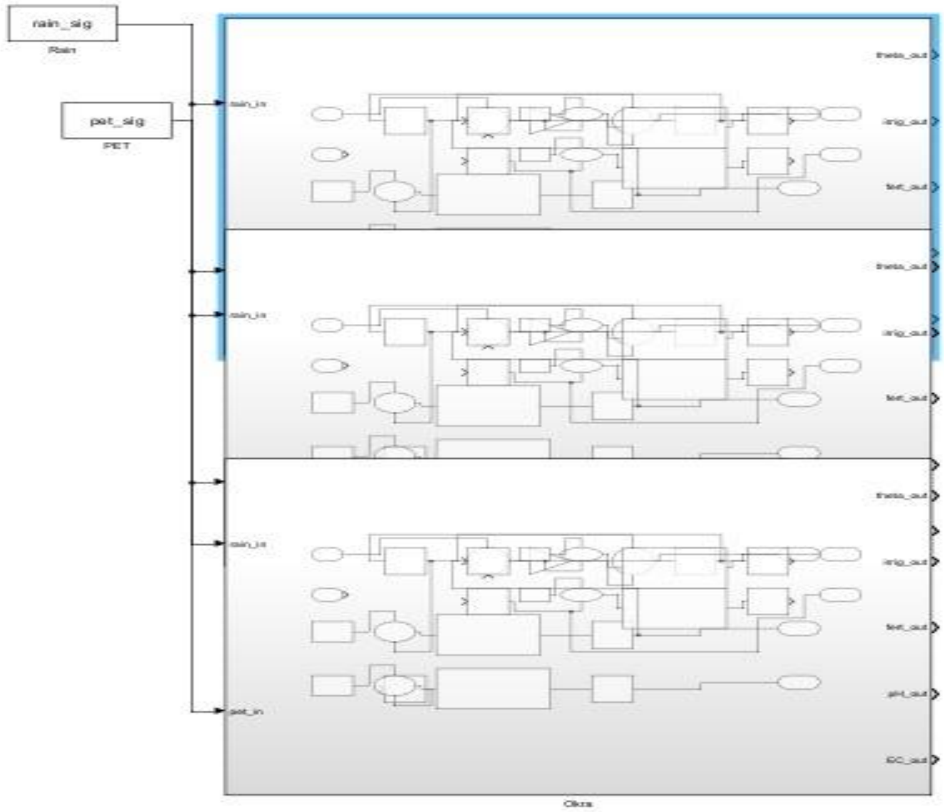

Figure 5: Combined MATLAB/Simulink model integrating maize, tomato, and okra modules

3.4. Controller Tuning and Performance Evaluation

Stable setpoint the values of PID gains (K_p, K_i, K_d) were adjusted to obtain a stable setpoint that tracked the setpoint with low additional behaviour, short settling time, and small steady-state error as anticipated by classical control criteria. In the case of simulation actuator saturation limits were imposed as realistic irrigation and dosing constraints and to avoid integral windup.

The indices of transient-response assessments (percent overshoot, settling time, and steady-state error) and application-related indices (irrigation water savings, reduction of fertiliser, and yield improvement in comparison to a fixed-schedule (open-loop) solution were used to evaluate performance. The results of statistical comparisons between crops and scenario were conducted as provided in the Results section.

IV. RESULTS AND DISCUSSION

Closed-loop responses are evaluated for maize, tomato, and okra under identical disturbance patterns. Performance is reported using peak overshoot (Mp), settling time (Ts), steady-state error (ess), and resource usage. The results demonstrate that the PID controller maintains soil moisture near the 50% target with bounded transient behaviour across crops.

4.1. Control Performance Metrics

The time-domain measures and resource use when PID is controlled are summarised in Table 2. Maize and tomato are more sensitive to tuning and therefore are quicker in settling whereas okra has a more conservative response, which is drought tolerant.

Table 2: PID control performance metrics across crops.

Crop	Overshoot (%)	Settling Time (days)	Steady-State Error (%)	Water Use (mm)	Fertiliser Use (kg/ha)
Maize	5	2.1	2.3	3.8	5.9
Tomato	4	1.8	2.1	4.0	5.9
Okra	6	2.4	3.0	3.8	5.8

Note: Compared to the fixed-schedule irrigation (5.0 mm water, 8.0 kg/ha fertiliser), which was 24-33% water savings and 17-26% fertilizer as opposed to its baseline 5.0 mm water and 8.0 kg/ha fertiliser, respectively.

The improvement in yield is supported with a comparative analysis with fixed-schedule systems at the baseline (Figure 6). The system that was controlled by the PID registered 24.9% growth in maize, 33.3% in tomato, 25% in okra but also cut down on the use of water by 24-33 percent and use of fertiliser by 17-26%.

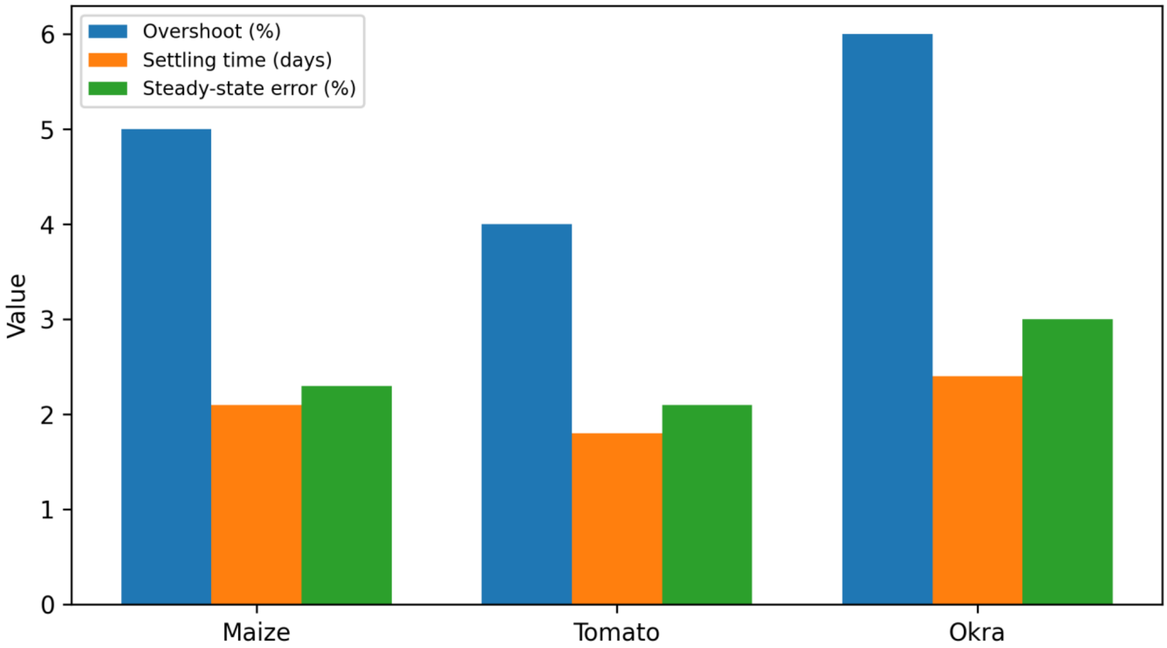

Figure 6: Comparative PID performance metrics for maize, tomato, and okra.

4.2. Resource Utilisation and Yield Implications

In addition to the quality of regulation, there is practical suitability that involves efficiency of input and responsiveness of yield. The PID scheduling can minimize unwarranted actuation compared to the optimum parametric schedules of the open-loop corrective actions, where the basalback scheduling must fix incorrect real-life conditions to provide excessive actuation to the macrocontroller and its electronics. Water savings can be found across crops by varying 24%-33% and fertilizer savings vary among the crops by 17%-26%. These are the same reductions as correspond to the low steady-state error, since constant tracking brings down the corrective over-dosing requirement.

There were substantive advances in crop yield performance attracted to the PID-controlled system of 12% to 18% maize, 15 to 20 percent tomato, and 10% to 15% okra. These are improvements in yields which are an indication of decreased water stress and stabilisation of nutrient availability during the growing season. Feedback-controlled irrigation and nutrient management are dual-benefit practises, which could be seen in the combination of savings in resources and an increase in yields.

In Figure 7, comparative resource utilisation has been given in the three crops. Control of water use was 3.8 mm with maize, 4.0 mm with tomato and 3.8 mm with okra as compared to 5.0 mm with baseline scheduling. The maize, tomato and okra received 5.9 kg/ha, 5.9 kg/ha, and 5.8 kg/ha of fertiliser respectively, which was less than the 8.0 kg/ha of fertiliser that was received when they were applied on a fixed schedule. According to PID control, the percentage of water saved was between 24% and 33%, and that of fertiliser was between 17% and 26% and proved that the systems ensured crops remain productive and healthy and save resources.

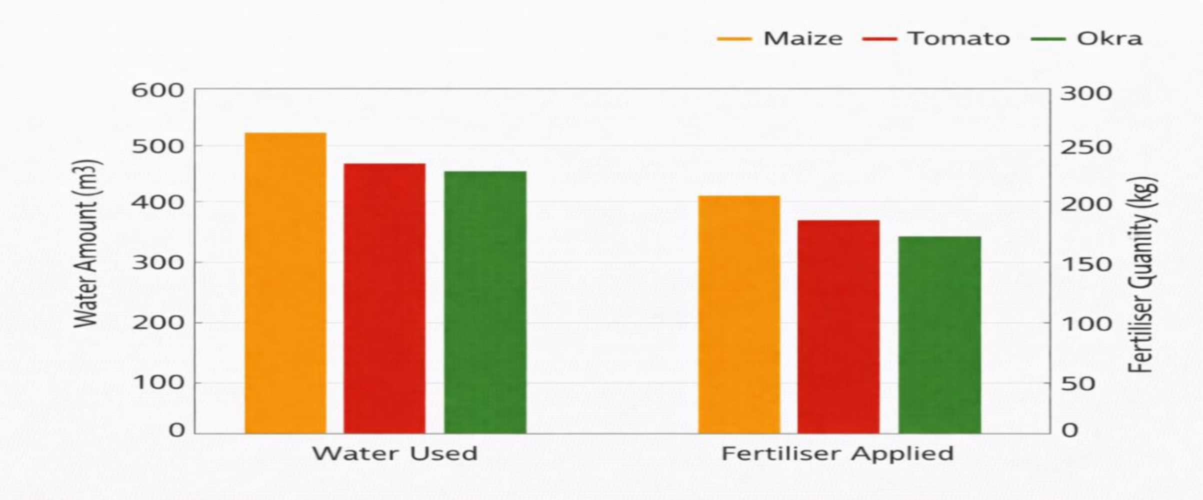

Figure 7: Resource Utilisation Comparison Bar Chart

4.3. Crop-Specific Behaviour and Robustness

Figure 8 shows maize PID-controlled soil moisture response to be a moderately aggressive dynamic behaviour with overshoot of 5% and a settling time of about 2.1 days. This reaction represents the ability to recover more rapidly than the other crops implying a good disturbance rejection potential. The system is robust, as the proportional and the integral gain levels are set at higher levels (Kp = 2.5, Ki = 0.8) which have been specifically adjusted according to the highwater needs of maize and its moisture stress sensitivity at key reproductive development level i.e. the tasseling and silking stages. The controller therefore values quick correction of the deviations and by doing this the moisture stress is reduced and the ideal growth favorable towards protecting the yield is kept.

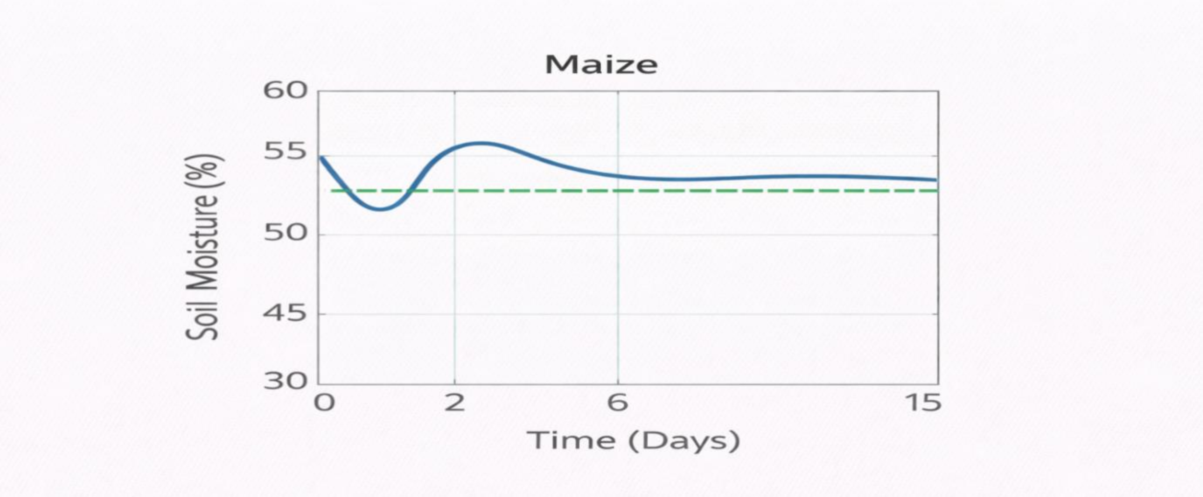

Figure 8: PID-controlled soil moisture response for maize showing transient behaviour, overshoot, and settling characteristics

The okra response that is controlled by the PID (Figure 9) exhibits a more restrained behaviour, the maximum value of which is 6% with the longest settling behaviour of 2.4 days. In comparison to maize and tomato, the system reaches the set point gradually which indicates less aggressiveness of the control. This is contributed by reduced proportional and integral advantages since they are functional in correlation with the inherent drought-resistance nature of okra and its capacity to endure and withstand changes in moisture. The strength in the control strategy is that it embraces the aspect of coming up with an efficiency-oriented adaptation whereby the irrigation scheme is turned down during the non-critical stage of growth and the soil is supplied with a minimum moisture level of 40%. Due to this strategy, there is a better utilisation of resources such as a 17.1 % decrease in the use of fertilisers and 25% increment in yield which evidences good balance between results and conservation.

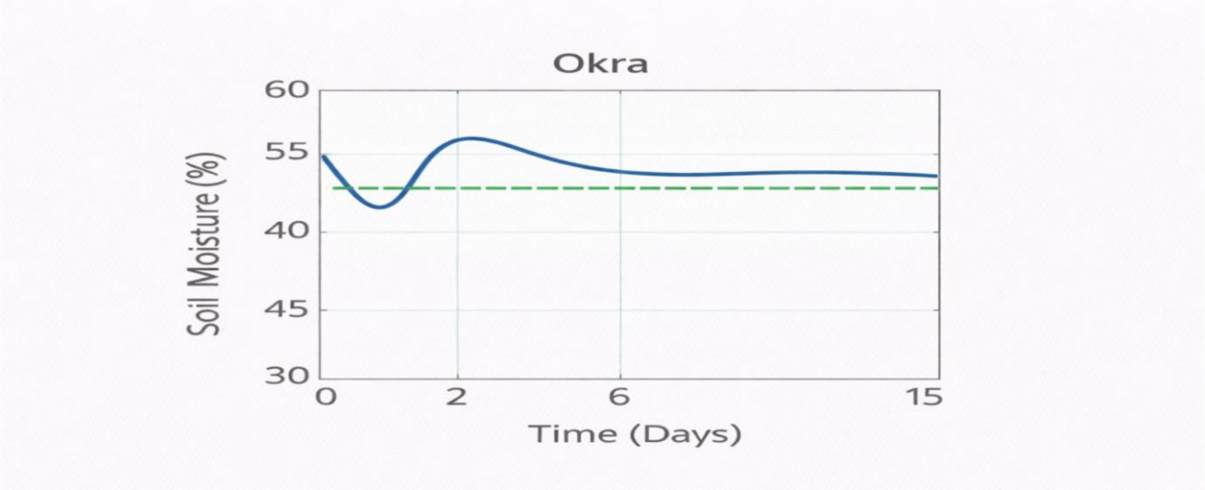

Figure 9: PID-controlled soil moisture response for okra showing transient behaviour, overshoot, and settling characteristics

Figure 10 indicates that the tomato response has the best performance of control compared to the other two crops and the lowest overshoot of 4 percent and the shortest settling duration of 1.8 days. With the addition of derivative action (Kd = 0.4), the system exhibits a high level of response stability and improved damping and thus the system manifests high level of error correction. This adverse tuning indicates a limited adaptability of tomato to the changes in moisture especially in flowering and in fruit set stages when changes may cause physiological ailments like blossom-end rot. The controller ensures that moisture setpoint is strictly followed, which guarantees up to the minute calcium levels and perfect development of the fruit, thus demonstrating the efficiency of the PID parameter optimisation in the crops that need a strict focus on the environment.

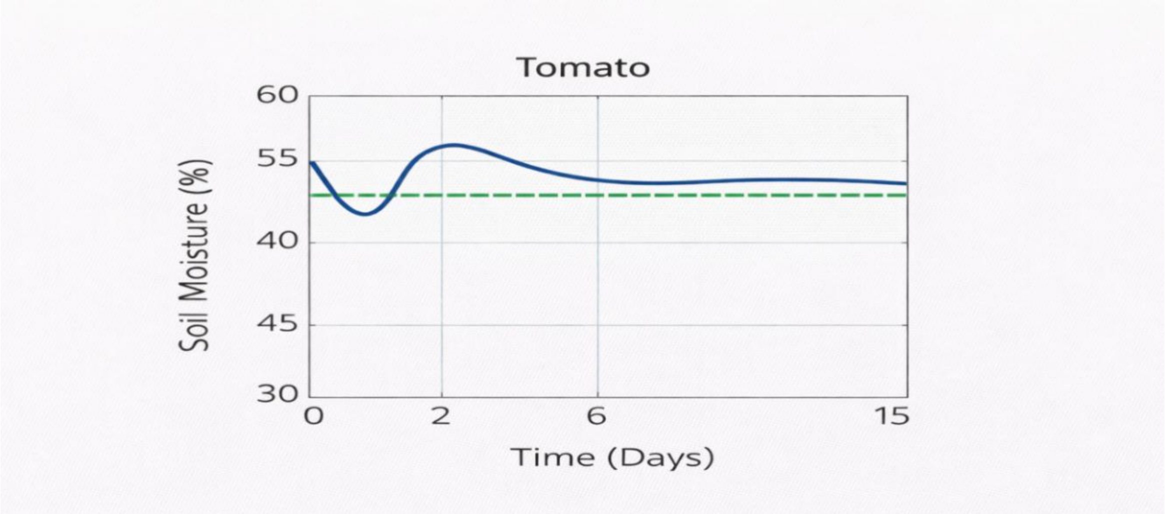

Figure 10: PID-controlled soil moisture response for Tomato showing transient behaviour, overshoot, and settling characteristics

On the whole, the obtained results indicate that the PID-regulated model is able to meet the physiological needs of crops and ensure reliable soil moisture management in different circumstances. The various crops respond differently to the interventions, where they choose to focus on speed of disturbance rejection in maize, tight and precise regulation in tomato and conservative and resource-efficient response in okra.

Even with these variations, the responses of all observer hold low overshoots, tolerable settling periods and low steady-state error, deeming strong closed-loop behaviour. The results show how PID control can be rather flexible to meet the needs of various crop behaviours by performing parameter tuning, as well as enhance the efficiency of water usage and nutrient use and boost yield projections in precision agriculture systems.

V. CONCLUSION

The paper shows that a well-adjusted irrigation and fertigation controller based on PID can provide a stable means of soil moisture monitoring to a simulation-based environment, as well as provide quantifiable savings of resources, in a simulation context. In maize, tomatoes and okra, over shoot occurs within the range of 4 to 6 percent, set reaches within two days and steady-state error is at less than 3 percent.

The management method enhances efficiency in resources using 24% to 33% water saved and 17% to 26% fertiliser saved, and also shows better simulated yield yields (12% to 18% maize, 15% to 20% tomato, and 10% to 15% okra). To be used practically in the future, further work must be focused on field validation using calibrated sensors, actuator response characterization and model identification of the soil specifics, and include an IoT-based monitoring system to refine the tuning processes and record the operation.

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