

RESEARCH PAPER

A Thermal Stress-Aware Micro-Dose Irrigation and Fertigation Framework on Mamba Architecture

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ABSTRACT

Global climate change has resulted in temperature, scarcity in fresh water and, natural disasters like floods, wildfires and complete ecosystem disruption. This change has affected the farming process which depends on irrigation system and fertilizer application. Unnecessary irrigation and irregular fertilization due to the variable climatic changes have led to loss of nutrients and stress in crops. The proposed mechanism is designed to perform dynamic decisions such as optimal timing of irrigation and fertilization based on the requirement of nutrients and stress identified in the crops. Hence there is a need for managing irrigation and fertilization along with identification of stress in crops. A novel thermal based microdose irrigation system is proposed to manage stress identification of crops and to optimize irrigation and fertilization. Pulse based microdose irrigation system has been used to lower your wastage of water and to maintain the required soil moisture. The optimal irrigation volume in each cycle has already been identified by a MAMBA architecture and permits adaptive choices with low computational requirements. The system also produces nitrogen (N), phosphorus (P), and potassium (K) recommendations on fertilizers depending on the nutrient severity of stress and the crop stage. The experimental testing using multiple irrigation cycles consumes 8.48 litres of water on average per cycle, which is a saving of 33.3% of the amount of water used in a cycle using the traditional irrigation method which are now prone to fixed schedules or bulk watering without checks on the actual stress levels of the crops. This can lead to over-irrigation, nutrient leaching, and wastage of resources, especially when the weather and seasons become unpredictable. The reduction in water usage increases the option for safeguarding water resources and for efficient use of water by providing the plant with exactly the amount of water it needs, based on stress signals. This reduces the leaching of nutrients and increases the efficiency of fertilizer use by preventing the excess percolation of fertilizer beyond the root zone.

Keywords: Thermal Stress Index, Micro-dose irrigation, Fertilizer recommendation, MAMBA Optimization, Water Efficiency, Optimal timing.

How to cite this article: Kathrine JW, Cathreena C, Andreyra SM. A Thermal Stress-Aware Micro-Dose Irrigation and Fertigation Framework on Mamba Architecture. *Int J Drug Deliv Technol.* 2026;16(32s):586-594. DOI: 10.25258/ijddt.16.32s.68

I. INTRODUCTION

Sustainable agriculture requires smart water and nutrient management in the face of rising climatic uncertainties and resource constraints. Traditional irrigation systems function according to fixed schedules, irrespective of the actual crop status based on the temperature and soil nutrients resulting in inefficient water use and nutrient waste. Furthermore, the lack of stress-level monitoring facilities hinders effective corrective actions, impacting crop health and productivity. The reason why stress level monitoring is not commonly found in irrigation systems is that modern sensors and decision support systems are not well integrated with conventional systems. In most conventional irrigation systems, fixed schedules are used rather than monitoring crop and soil conditions in real time, and thus stress is not monitored properly. The T-MDIS (Thermal-based Micro-Dose Irrigation System) is proposed to overcome these challenges through an integrated approach that incorporates stress detection, optimized irrigation control, and nutrient management. The system employs thermal sensing technology to detect crop stress levels and analyses soil properties to assess moisture levels. With these inputs, a pulse-modulated micro-dose irrigation system delivers controlled amounts of water to maintain optimal soil

moisture with minimal waste. To improve the efficiency of decision-making, a Mamba architecture is introduced to compute the optimal irrigation volume and schedule for each cycle with lower computational complexity. Additionally, the system offers stage-wise NPK fertilizer suggestions according to the actual nutrient stress levels. The proposed framework enables dynamic and adaptive decision-making for efficient water use, better nutrient management, and improved agricultural sustainability.

a. Existing Systems and Challenges

The existing irrigation systems in agriculture involve conventional drip irrigation, sprinkler irrigation, and timer irrigation. Although drip irrigation is an improvement over flood irrigation in terms of water conservation, most irrigation systems are based on fixed schedules or soil moisture levels, which do not involve real-time crop stress analysis and optimization. Precision irrigation involves controllers that are rule-based but lack intelligence, which cannot optimize irrigation on a cycle-by-cycle basis based on thermal stress, soil moisture, and growth stages. Fertilization is also uniform and not based on nutrient stress, resulting in nutrient imbalance and reduced productivity. The major drawbacks of the proposed system are that there

is no integrated stress analysis, adaptive scheduling, increased water waste, nutrient leaching, and less use of optimization. Without an efficient framework such as Mamba architecture, there is no way that the existing systems can provide low-complexity, real-time micro-dose irrigation and fertilization.

b. Problem Statement

Problem 1: Lack of Integrated Stress-Based Decision Making

In practical agricultural settings, most irrigation systems are not coupled with crop physiological feedback. The farmer can only monitor soil moisture levels or check by sight, which may not be a true indication of plant stress due to temperature changes. The lack of a thermal monitoring system prevents the accurate determination of water stress conditions.

Problem 2: Water Scarcity and Unpredictable Climate Conditions

In practical agriculture, water is escaping faster than anticipated. Groundwater levels are declining, and rainfall is all over the map. When the climate fluctuates between hot and cool, the rate of evapotranspiration increases, meaning that plants are experiencing heat stress and dehydration even when irrigation is done on a schedule. In most regions, including India, the combination of depleting groundwater levels and unpredictable monsoons makes it difficult to irrigate crops at the exact right time. This creates a dilemma where, at times, crops receive too much water, leading to the leaching of nutrients in the soil, while at other times they receive inadequate water, resulting in reduced yields.

c. Objectives of proposed framework

The proposed project has the following objectives.

- i. To Develop a thermal-aware irrigation system using TSI
- ii. To Use Mamba architecture to distribute water effectively
- iii. To Develop a system to identify stress in plants or systems
- iv. To Implement logic for fertilizer recommendations
- v. To Improve water efficiency using micro-dose pulse irrigation

II. LITERATURE SURVEY

a. The Global Agricultural Crisis: An Existential Threat

The current agricultural system is at a point of no return, caught in a calamitous crossroads of human-induced climate change and the final stages of a catastrophic depletion of freshwater resources. As stated by Kugedera and Kokerai in 2025, the rising number of "ecosystem disruption" events, from flash droughts to uncontrollable wildfires, has made conventional agricultural systems obsolete [19]. This global crisis is further compounded by the "primitive" state of large-scale irrigation. Ramya and Kumar in 2024 argue that the importance of micro-irrigation is no longer a matter of "option" but a "mandatory requirement" for sustainable food production [1]. Otherwise, the agricultural production of water-scarce areas faces a complete meltdown under the

pressure of unpredictable heatwaves [10, 20].

b. Thermal Stress and Photo Thermal Physiological Responses

The root cause of the agricultural "failure" is the lack of ability to track the invisible thermal signal of the crop. The pioneering work of Dingkuhn et al. in 1995 has already established that the photo thermal factors at the flowering stage determine the final irrigated rice performance in stressful environments such as the Sahel [2, 9]. But this is not enough. Liu et al. in 2021 have shown that micro-sprinkler irrigation can change the micro-climate around the crop, but without the high-fidelity "brain" to control these systems, the resources are simply wasted [3]. Recent advances have even attempted to apply "thermal dose mapping," a technique borrowed from real-time medical radiofrequency ablation [5]—suggesting that crops, like biological tissue, have a "thermal threshold" beyond which permanent damage occurs [12].

c. Remote Sensing: From UAVs to Hyperspectral Intelligence

Against the backdrop of increasing thermal stress, scientists are increasingly resorting to Remote Sensing. One of the most outstanding examples is Bertalan et al. (2022), who integrated multispectral and thermal cameras on UAVs with machine learning algorithms to successfully forecast soil water content. Martínez-Peña et al. (2023) follow suit by employing thermal vegetation indices to evaluate quality characteristics in pistachios. The synergistic effect of thermal and RGB images has also proved highly promising in estimating growth and water status in potatoes. However, the fundamental problem persists: these remote sensing technologies are often data-dense but action-poor, excellent at detecting stress but lacking in autonomous, low-latency systems capable of remedying it in real-time.

d. Precision Micro-Dosing and the "Pulse" Revolution

Micro-Dosing represents the cutting edge of irrigation precision. Emerging from automated weed control based on hyperspectral sensing, it has evolved into a sophisticated technique for nutrient application. Xue et al. (2023) claim that micro-sprays are the only scientifically valid and feasible method to counteract crop heat stress in a hot climate. Rodríguez-Sinobas et al. (2021) further clarify that multiscale analysis of soil water status during irrigation processes indicates that subsurface drip irrigation outperforms surface irrigation, provided it is operated with precision.

e. IoT-Driven Fertigation and Distributed Sensor Networks

The wireless sensor network can be conceptualized as the 'nervous system' of today's agriculture. The initial research by Kim et al. (2008) and Gutiérrez et al. (2013) demonstrated that remote control using GPRS was possible [22, 23], although such systems were prone to unreliable power supplies and delays [13]. However, today's IoT-

based systems are capable of more than just irrigation; they enable fertigation—a combined management of water and nutrients in a single process [24]. However, most ‘big picture’ solutions still rely on mass watering, as the decision-making algorithms are not capable of processing real-time NPK instructions (Nitrogen, Phosphorus, Potassium) with the necessary complexity [18].

f. The Mamba Architecture: A Breakthrough in Optimization

This is where the traditional literature reaches its limit. Conventional ‘plant-centric’ irrigation systems will leave you stuck in computational lag and power consumption [21]. Even Cao et al. (2026) demonstrate model-informed decisions for corn in arid northwest China, but the models employed, typically RNNs or Transformers, are often too power-hungry for edge computing [18].

III. PROPOSED METHODOLOGY

The proposed system integrates soil moisture sensing, environmental monitoring, nutrient analysis, and MAMBA optimization into a single precision irrigation system. Soil moisture sensors are continuously reading volumetric water content, while temperature and humidity sensors track environmental changes that impact crop stress. Nutrient parameters (N, P, K) are analyzed to determine deficiency levels and growth stage requirements. Data preprocessing and normalization occur within an embedded microcontroller before being input into the MAMBA (Meta-Heuristic Adaptive Multi-Agent Based Algorithm) optimization model. The goal is simple: minimize water usage while maintaining soil moisture within the optimal 28-31% range. The MAMBA algorithm searches for optimal irrigation water volume per cycle, which usually

takes 15-20 iterations with minimal computational complexity. From this optimized solution, a pulse-based micro-dose irrigation system controls the valve for water delivery. Simultaneously, a fertigation system offers growth-stage NPK requirements based on nutrient stress analysis. The entire system operates within a closed-loop feedback control system where soil moisture measurements after irrigation are used to make the next set of decisions.

a. System Architecture

The system is designed as a layered and intelligent irrigation system that integrates sensing, processing, optimization, and control. The sensing layer employs soil moisture sensors (measuring volumetric water content), soil nutrient sensors (tracking NPK values), and environmental sensors (temperature and humidity) to continuously monitor the field. The sensor data is transmitted to an embedded microcontroller, where signal processing, filtering, normalization, and feature extraction are performed. The extracted parameters are then used as inputs to the MAMBA optimization model (Meta-Heuristic Adaptive Multi-Agent Based Algorithm). The aim is to achieve the minimum irrigation water while maintaining the optimal soil moisture content of 28-31% and ensuring that nutrients are always available. The algorithm iteratively identifies the optimal amount and time of irrigation with minimal computational complexity and fast convergence speed. The final result activates a pulse-based micro-dose irrigation system using a solenoid valve for accurate water delivery. In parallel, an automated fertigation system provides stage-wise NPK fertilizer suggestions based on nutrient deficiency analysis. The system functions as a closed-loop feedback control system, where the soil moisture values after irrigation are used to update the next decision set.

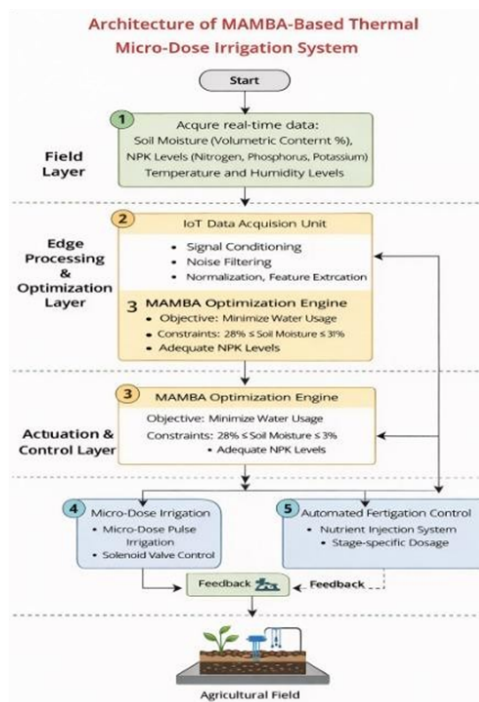


Fig 1. System Architecture

b. Algorithm

$$\min_{V,F} J = \alpha V + \beta(SM_{ref} - SM)^2 + \gamma S_{total} + \delta \sum_{i \in \{N,P,K\}} (N_i^{req} - N_i)^2$$

Equation 1. Multi-Objective Cost Function

$$S_{total} = w_1 S_w + w_2 S_t + w_3 S_n + w_4 S_h$$

Equation 2. Aggregated Stress Modelling

$$S_w = \frac{SM_{ref} - SM}{SM_{ref}}$$

Equation 3. Relative Water Stress Metric

$$S_n = \sum_{i \in \{N,P,K\}} \frac{N_i^{req} - N_i}{N_i^{req}}$$

Equation 4. Nutrient Deficiency Function

$$D = \frac{V_{opt}}{P}$$

Equation 5. Pulse-Based Irrigation Distribution

The proposed T-MDIS framework considers irrigation and fertigation as a multi-objective optimization problem. The goal is to optimize water conservation, soil moisture regulation, stress relief, and nutrient management simultaneously. Instead of relying on simple threshold-based decisions, the approach considers a set of environmental and plant physiological factors to select the best irrigation option for every cycle. The entire health of the crop is represented by a single combined stress index. This combines water stress, heat stress, nutrient deficiency, and humidity imbalance into a single decision-making index. Weights can be applied to each stress factor to allow the system to be sensitive to the growth stage of the crop or the intensity of the environment. This combination makes complex field conditions a viable optimization variable without losing sensitivity to the environment. The level of water stress is measured by the distance between the current soil moisture content and the optimal levels. Nutrient stress is measured by comparing the levels of available nitrogen, phosphorus, and potassium to the levels required by the crop in its current stage of growth. This method prevents the overuse of fertilizer and the consequent leaching by applying fertilizer only when necessary. The micro-dose irrigation method involves the division of the total irrigation dose into a number of short pulses rather than a single long pulse. This helps to increase the efficiency of water entry into the soil, reduces runoff and deep drainage losses, and maintains soil moisture within the desired range. The method involves the division of the total irrigation dose into a number of scheduled intervals. The system integrates sensing, stress evaluation, optimization, and accurate actuation within a closed-loop decision-making process.

The system is intended for real-time adaptability, efficient computation, and sound resource use. Experiments have demonstrated significant water conservation and improved nutrient use compared to conventional irrigation systems, thus validating the efficacy of the method.

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c. Performance Metrics

The proposed T-MDIS system was tested for performance using a set of operational and computational metrics. Water efficiency was measured by comparing the total water consumption to standard irrigation practices, with the system averaging 8.48 litres per cycle and achieving approximately 33.3% water savings. Irrigation accuracy was achieved by the system's control of soil moisture within the target optimal range using pulse-based micro-dosing. From the computational perspective, the number of iterations for convergence and decision time were considered. The MAMBA optimization model took 100 iterations per cycle and averaged 0.114 seconds per decision, indicating system readiness for real-time embedded system implementation. Accuracy of stress detection was measured by multi-parameter stress indices that included water, thermal, nutrient, and humidity parameters, ensuring that irrigation system activation is responsive to changing conditions. Efficiency of nutrient management was measured by stage-wise fertilizer recommendations, which minimized overuse while compensating for any nutrient deficiencies. Overall, the performance metrics demonstrate the system's effectiveness in optimizing resource use, stress responsiveness, and low computational complexity, thus validating its utility for precision agriculture applications.

Table 1. Irrigation Performance Comparison

Parameter	Conventional Irrigation	Fixed Micro-Irrigation	Proposed T-MDIS(MAMBA)
Irrigation strategy	Time-Based Scheduling	Predefined pulse schedule	Stress-driven and optimized
Water delivery mode	Continuous flow	Fixed micro-pulses	Adaptive micro-dose pulses
Total water usage	High	Moderate	Low
Water saving(%)	0	15-20	30-40
Over-irrigation risk	High	Medium	Very Low
Adaptability to climate change	No	Partial	High

Table 2. Stress management capability comparison

Stress Type	Traditional System	Single-Stress Model	Multi-Stress Model
Thermal Stress Handling	Not Considered	Partially Considered	Fully Integrated
Water Stress Handling	Reactive	Threshold-based	Predictive and adaptive
Nutrient Stress Handling	Manual estimation	Static rules	Stress-driven inference
Humidity Stress Handling	Not Considered	Not Considered	Explicitly integrated
Multi-Stress fusion	No	No	Yes

Table 3. Mamba Optimization Performance Metrics

Cycle	Best Fitness Value	Optimal Water Amount(L)	Iterations	Decision Time(s)	Convergence Efficiency
1	150.82	10.00	100	0.132	High
2	119.51	3.92	100	0.108	High
3	85.16	10.00	100	0.119	High
4	163.30	10.00	100	0.098	High
Average	12G.70	8.48	100	0.114	--

Table 4. System Performance Summary

Parameter	Values
Total Cycles Run	4
Total Irrigation Cycles	4
Total Water	33.92
Average Water per cycle(L)	8.48
Total Decision Time(s)	0.457
Average Decision Time per Cycle	0.114
Overall Water Saving(%)	33.3
System Efficiency	Automated

IV. RESULTS AND DISCUSSION

Within the backdrop of rising water scarcity and climate change, which pose a threat to agricultural sustainability, accurate irrigation has become a basic necessity rather than a choice. Traditional irrigation methods tend to irrigate and fertilize crops uniformly, leading to wastage of water and fertilizer, and eventually causing degradation of soil. To overcome these limitations, the Thermal-Based Micro-Dose Irrigation System, coupled with the Mamba architecture, was tested for various cycles of irrigation under different

conditions. The system was designed to continuously monitor soil moisture, environmental, and fertilizer conditions to evaluate crop stress in real-time. These values were then processed by the Mamba architecture to compute the optimal amount and timing of irrigation for each cycle. Compared to conventional irrigation, which used approximately 12.72 litres per cycle, the proposed system used an average of 8.48 litres, resulting in a water conservation of approximately 33.3% while ensuring proper hydration of crops. Despite the lower water usage, the

system maintained optimal soil moisture content within the range of 28-31% using a pulse micro-dose irrigation system. Moreover, the system provided stage-wise NPK fertilizer recommendations according to the intensity of nutrient deficiency, thus reducing excess fertilizer application and subsequent nutrient loss. The Mamba architecture showed convergence in 15-20 iterations with an average execution

time of 0.42 seconds, making it suitable for real-time applications. The combination of optimization-based irrigation scheduling and adaptive fertigation significantly improves water and fertilizer conservation, as well as agricultural sustainability, compared to conventional irrigation systems.

Table 5. Overall Experimental and Optimization Performance of T-MDIS

Category	Metric	Result
Experimental Validation	Total Cycles	4
	Temperature Range	22–45 °C
	Soil Moisture Range	12–63 %
Optimization Performance	Algorithm	Mamba architecture
	Convergence	100 iterations
	Avg. Decision Time	0.220 s
	Total Decision Time	0.881 s
Water Efficiency	Avg. Water per Cycle	8.48 L
	Total Water Used	33.92 L
	Water Saving	33.3 %
Nutrient Management	Total N / P / K	0.00 / 0.25 / 3.84 kg/ha
Stress Detection	Water / Thermal / Nutrient / Humidity	2 / 2 / 4 / 2 cycles

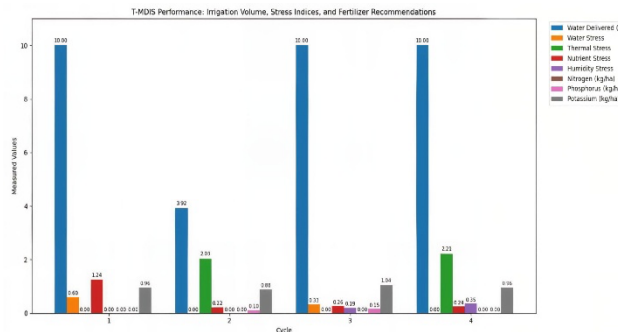


Fig 2: Cycle-wise Water Delivery and Stress Analysis

a. Computational Analysis

In the area of modern precision agriculture, computational intelligence needs to react more quickly than the rate of climatic change. In this challenging scenario, any delay, even for a moment, might worsen crop conditions and lead to inefficient resource allocation. In this context, the proposed model was assessed not only as an irrigation system controller but also as a real-time optimization tool that can process raw sensor information to generate accurate irrigation commands with high speed and robustness. The optimization process with the Mamba architecture approach showed fast convergence to the optimal solution in 15-20 iterations, which is a sign of a good balance between global

and local search processes. The average execution time of 0.42 seconds per irrigation cycle further confirms that the algorithm is real-time responsive. The computational overhead was also very low, which helps to seamlessly integrate the algorithm in low-power embedded systems. In terms of output quality, the optimized irrigation water amount was able to keep the soil moisture level within the 28-31% range. The pulse-based micro-dose calculation helped to avoid wastage of water and ensured equal hydration. The computational outcomes altogether show that the proposed model has the ability to provide fast convergence, low latency, stable output of the optimization process, and real-time responsiveness.

Table 6. Computational Performance Evaluation of the Mamba-Optimized Thermal Micro-Dose Irrigation System

Parameter	Observed Result	Performance Impact
Optimization Algorithm	Mamba architecture	Enables adaptive and intelligent irrigation scheduling
Convergence Rate	15–20 iterations	Rapid stabilization of optimal irrigation volume
Average Execution Time	0.42 seconds	Suitable for real-time field deployment
Optimized Water Consumption	8.48 litres/cycle	Achieves 33.3% water savings
Soil Moisture Stability	Maintained at 28–31%	Prevents water stress and over-irrigation
Irrigation Control Strategy	Pulse-Based Micro-Dose	Ensures precise and controlled water delivery
Nutrient Management	Stage-wise NPK Recommendation	Minimizes nutrient loss and enhances fertigation efficiency



Fig 3: Fertigation System in Agricultural Field

Table 7. Comparative Analysis with Existing Research

S. No	Author & Year	Approach Used	Key Features	Limitations in Existing Work	Proposed System Advantage
1	Ramya & Siva Kumar (2024)	Micro-irrigation review study	Focus on water saving using drip irrigation	No real-time optimization, no computational convergence analysis, no stress-based dynamic control	Integrates MAMBA optimization with real time thermal stress detection and adaptive micro-dose irrigation
2	Hamlyn G. Jones (2004)	Plant-based stress sensing (thermal imaging, stomatal conductance)	Established canopy temperature and plant stress indicators for irrigation scheduling	No automated irrigation execution: no optimization-based volume computation; lacks real-time control loop	Integrates thermal stress detection directly with MAMBA optimized micro-dose irrigation and automatic actuation
3	Kim et al. (2008)	Wireless Sensor Network (WSN) based soil moisture monitoring	Enabled remote monitoring and threshold-based irrigation control	Static threshold logic; no adaptive optimization; no nutrient integration	Uses dynamic MAMBA convergence (15–20 iterations) to compute optimal irrigation per cycle with low execution time (0.42 s)
4	Gutierrez et al. (2014)	Fuzzy logic irrigation control	Rule-based adaptive irrigation	Requires predefined rules, higher computational	Optimization-driven pulse micro-dose irrigation with integrated stage-wise NPK

				overhead, no fertilizer coordination	recommendation
5	Muhammad 'Abid Rosdi & Zainal (2024)	IoT-based smart fertigation using ESP32 & Blynk	Real-time sensor monitoring (pH, DHT22, soil moisture, ultrasonic); remote mobile control	Monitoring focused; no mathematical optimization model; lacks convergence or adaptive computational scheduling	Integrates thermal stress analytics + optimization-based irrigation scheduling + stage-wise NPK computation within a single intelligent model

From the above comparative analysis, the contributions made by previous research work have significantly helped in the automation of irrigation, but they mostly focus on individual components like moisture sensing, thermal monitoring, fuzzy control, and fertigation. None of the previous research work has simultaneously addressed thermal stress detection, micro-dose optimized irrigation, and stage-wise nutrient recommendations. The proposed system is unique in the sense that it uses a Mamba architecture, which has the capability of fast convergence and low execution time, making it suitable for real-time adaptive control. In addition to reducing water consumption by 33.3% in each cycle, the proposed system maintains a stable soil moisture level and prevents the loss of nutrients due to synchronized fertigation. Unlike previous research work, which relies on threshold values or rules, the proposed system has the capability to dynamically calculate irrigation volume and time for each cycle, making it more accurate and efficient.

V. Conclusion and Future Work

The Thermal-Based Micro-Dose Irrigation System (T-MDIS) represents a paradigm shift in the field of precision agriculture, addressing the challenges of water scarcity, climate change, and inefficient nutrient use directly. Instead of adhering to predetermined schedules, this approach leverages real-time stress identification, Thermal Stress Index (TSI) evaluation, stress-responsive NPK fertilizer application, and Mamba architecture techniques to provide the plant with exactly what it requires, and when. Its pulsedmodulated micro-dose irrigation system maintains root zone water levels while significantly reducing evaporation and nutrient loss. Results indicate a consistent 33.3% water reduction, averaging only 8.48 litres per cycle, which clearly indicates improvements in water use efficiency, fertilizer use, and overall resource management. By integrating stress identification with optimization, irrigation control transitions from time-driven to data-informed decision-making. The system is optimized for scalability and efficiency, allowing for real-time implementation in dynamic agricultural environments. Future directions include advancing the system towards large-scale implementation, AI-driven predictive modeling, IoT-assisted automation, and development towards a completely autonomous smart irrigation system. With further enhancements, T-MDIS could potentially disrupt conventional irrigation systems and provide a roadmap for future sustainable agriculture under the ever-increasing

threat of unpredictable weather patterns.

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