American Journal of Bioscience and Clinical Integrity
https://biojournals.us/index.php/AJBCI
ISSN: 2997-7347

A Patent-Oriented Architecture for Autonomous Irrigation Based on Plant Drought Stress Sensing and Wi-Fi-Enabled Decision Control

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Received: 2025, 15, Oct
Accepted: 2025, 21, Nov
Published: 2025, 20, Dec

Annotation: As climate change continues to intensify and impact future threat scenarios and climatic conditions, the efficiency and sustainability of agriculture will rely on improved climate adaptability and mitigation innovation, responses from irrigation scheduling, and the integration of water scarcity and uncertainties in climate and water availability. Most existing commercial smart irrigation systems utilize only single-variable soil moisture thresholds, which do not sufficiently capture the actual conditions of real-time plant water status. This research presents a patent-oriented architecture for autonomous irrigation scheduling based on detecting plant drought stress and Wi-Fi-enabled control, designed for real-time, closed-loop adaptive systems in genuine field conditions.

The customized architecture amalgamates the spatial arrangement of the sensor's deployment via distributed sensor nodes, where leaf surface temperature and optical soil moisture, soil moisture, and soil temperature of each crop are measured. Locally to each sensor, a composite Drought Stress Index (DSI) is formed from the water-stressed plant suppressive threshold. Sensor nodes periodically send DSI values to a central gateway using a low-power Wi-Fi communication approach. The gateway employs an adaptive decision algorithm that autonomously makes real-time control irrigation start, duration, and zone prioritization decisions based on managed DSI historical trends and plant response measured in DSI. Automated valve and pump control complete irrigation flow management, while all control operations are fully absent of human activity.

Field validation was done using a controlled experimental design involving three groups, manual irrigation, standard soil-moisture based irrigation, and DSI based systems. The assessment was based on total water use, temporal stress pattern, plant growth metrics, and final yield. The design was able to lower water use by 35-40% relative to manual irrigation, and by 18-22% relative to conventional smart irrigation, while keeping yield metrics the same or better. One- way ANOVA with P<0.05 showed that water use efficiency and stress stabilization improvements were significant. Also, abnormal DSI response patterns were able to automatically flag irrigation fault detections, flow blockage, and pump malfunction.

These findings indicate that the design is a scalable, energy efficient, and patentable solution to intelligent precision irrigation and sustainable agricultural water management.

Keywords: Autonomous irrigation control; Plant drought stress sensing; Wi-Fi sensor network; Precision agriculture; Drought Stress Index; Water-use efficiency.

Introduction

Currently, there are both climatic variability and prolonged periods of drought, which are causing multiple issues with global agricultural production and sustainability. As a result, strategic irrigation management is critical for mitigating agricultural drought. How agricultural water management is conducted is critical to how water is conserved while sustaining agricultural productivity. Unfortunately, during irrigation management, agricultural water managers typically use a schedule of intentional irrigation without considering factors such as weather and/or crop conditions. As a result, improper irrigation is frequently conducted. Improved irrigation management is using new technological advantages such as automated irrigation, wireless sensor networks and the IoT. Numerous agronomic research studies testify to the improvement of implemented technologies. However, the integration of technologies is still at basic levels, and the technological systems lack sufficient decision-making algorithms and plant physiological integration.

The majority of present-day smart irrigation practices rely almost exclusively on soil moisture measurements to decide whether to irrigate or not. Although soil moisture is an important indicator of water availability in the soil, under a given set of fluctuating environmental conditions such as high temperatures, radiation, or salinity, soil moisture in the root zone does not accurately reflect whether or not the plant is water stressed. A number of authors have shown that plant indicators such as leaf temperature, optical properties of the leaf, and radiation balance provide a more accurate measure of the water status of the plant than soil moisture alone [2,3]. The incorporation of such indicators of plant water status into irrigation control systems is a necessary step toward the implementation of more precise and ecologically relevant irrigation water management practices.

Recently, the use of composite stress indices, derived from different sensor inputs, to aid irrigation decisions has been gaining increased attention from scholars. Stress indices from smart crop systems have been shown to improve the precision to irrigation and diminish irrigation water use, especially in high-value crops like grape and horticultural systems [4]. At the same time, the advancements in infrared low-cost sensing, coupled with image-based analysis of the crops, have made the detection of plant stress feasible in field conditions [3]. However, many systems described in the literature still rely on the cloud, high computational demand, or non-Wi-Fi communication protocols, which could reduce scalability, and energy efficiency, and complicate the real deployment of the systems in agricultural environments.

Recently interest has started to focus on edge computing as well as autonomous control systems that learn the response patterns of plants over time. Gravimetric and edge-based IoT systems have shown the possibility of near real-time plant stress phenotyping and monitoring [5]. Review papers have also pointed to the need for fully integrated adaptive and energy efficient irrigation systems design that incorporate sensing, decision making, and actuation subsystems deployed within a single structure [6]. Despite the fact that there have been predictive models published incorporating advanced communication systems such as LoRaWAN and machine learning [7], there is still a substantial gap in what might be characterized as patentable or novel in the space of Wi-Fi communication, stress prototypes of plants, self-adaptive control, and a cohesive unit of irrigation for a deployed system.

This research presents a patent-oriented architecture for autonomous irrigation scheduling based on detecting plant drought stress and Wi-Fi-enabled control, designed for real-time, closed-loop adaptive systems in genuine field conditions.

Materials and Methods

Investigational Area & Agronomic Factors

The experimental research took place during an entire growing season and in an open-field agricultural environment. The chosen field location possessed parametrically uniform soil texture (clay loam), plain and level soil topography and homogeneously solar irradiated field location with respect to the soil to eliminate any diversions in spatial distribution. Before the installation of the systems, baseline agronomic procedures defined the soil attributes within the experimental units such as texture class and soil bulk density.

The crop under cultivation was sown in a uniform population across the entire field as per the local agronomical practices. All plots within the experiment received the same sets of fertilization, pest control, and weed management practices throughout the duration of the experiment. No rainfall-based compensatory irrigation was carried out, and all water utilized by the crops was solely and exclusively from the irrigation system under study.

Field Layout and Treatment Distribution

The field was partitioned into three irrigation zones, and each of the three zones was insulated from each other in terms of irrigation. The three zones were each assigned to one of the irrigation treatments:

Zone A (Manual irrigation): Irrigation time and duration were done by the farmer manually according to field observation of the crops and common practices.

Zone B (Conventional smart irrigation): Irrigation was done automatically with control to soil moisture level, and no plant-based sensing of the soil was used.

Zone C (architecture): The drought stress sensing in plants architecture offered autonomous control of irrigation. To avoid hydraulic interference, each zone operated separately, utilizing their own dedicated solenoid valves and flow meters to ensure accurate water measurement.

Sensor Node Hardware Configuration

Every sensor node comprised a unit of a low-power microcontroller with Wi-Fi integrated communication to 2.4 GHz. The microcontroller registered and communicated with the following sensors: A capacitive soil moisture sensor installed at a 15 – 20 cm depth to represent the active root zone. A soil temperature sensor placed at the same depth with the moisture probe to observe moisture-induced thermal effects. A non-contact infrared temperature sensor placed over the canopy of the crops to record the temperature of the leaf surface.

An optical sensor directed toward the crop canopies to measure changes in leaf color and reflectance of light. All sensor deployments involved calibration in accordance with procedures provided by the manufacturers and cross-validation to reference measures when appropriate.

Sensor Allocation as per Field Allocation

During each irrigation interval, sensor nodes were moved to avoid the border effect while representing the average field condition. Vertical inserts were made to the soil probes to guarantee steady contact with the surrounding soil. Leaf temperature probes and optical sensors were installed above the canopy at a fixed height and were protected from direct solar radiation which mitigate measurement artifacts.

The number of sensor nodes assigned per zone was chosen to ensure some degree of spatial representativeness with minimal system complexity. Nodes were provided with weatherproof housings and were powered with small solar panels and rechargeable lithium batteries which allowed them to function autonomously.

Data Collection and Sampling Methodology

Every sensor node operated according to a predetermined sampling schedule. In order to streamline communication, measurements were taken at 15 min intervals and aggregated at the sensor node. Raw sensor data were converted to a standard measurement and filtered to disentangle random noise. In the interest of drought stress estimation, only relevant processed data were sent to a centralized gateway.

As an energy conserving strategy, the sensor nodes entered a sleep mode of low power consumption between sampling rounds. Wi-Fi was only turned on during the data transmission periods of the sampling schedule.

Computing the Drought Stress Index (DSI)

At the sensor node level, a Composite Drought Stress Index (DSI) was calculated as a weighted average of the soil moisture deficit, the difference of leaf and air temperatures and the relative optical difference of canopy reflectance. Preliminary field observations were utilized to set the initial weighting coefficients empirically.

The DSI was normalized to a unitless scale to allow measurement and comparability across different zones and time periods. This index focuses solely on the plant’s physiological water stress rather than the availability of soil water.

Architecture for Wi-Fi Communication

Using a local Wi-Fi network, sensor nodes sent records of DSI values, node ID’s, timestamps, and battery levels to a central gateway. For the sake of battery conservation, the communication was limited to short data packets. The gateway acted as a local access point and data receiver, thus not relying on cloud computing or external internet access.

Data packets were received, checked for completeness, and stored in a local REAL TIME data base for immediate access, and in a structured manner, for the purpose of future data analysis.

Decision Logic and Central Gateway

A single-board computer, augmented with a DSI and control application, was assigned the central gateway. Aggregation of DSI values by irrigation zone was performed and then continuous monitoring was applied.

Irrigation decisions utilized zone-level DSI trends instead of single-point measurements. When the mean DSI of a zone crossed a dynamically adjusted threshold, irrigation was activated automatically. The irrigation duration was first set to a predetermined value, then adjusted based on the rate and magnitude of DSI diminution and recovery after irrigation.

This adaptive control strategy allowed the system to ‘learn’ the plant response behavior over time and to optimize water application without further human involvement.

Irrigation Control and Actuation

Every irrigation zone had electronically actuated solenoid valves linked to a common water supply. Valve actuation commands were received directly by the gateway via relay modules. A flow meter was also included at each zone inlet to measure the total water volume delivered during each irrigation event. For all treatments, irrigation timing, duration, and volume of water applied were recorded automatically.

Fault Detection and System Validation

The system was programmed to monitor post-irrigation DSI response. DSI values were not expected to stagnate or decline during a certain time, and this was read as an expected irrigation fault, including flow obstruction or pump failure. Fault events were logged and flagged, and these were noted on the system interface for maintenance checks.

Assessment of Plant Development and Productivity

Plants were examined at predetermined times to obtain primary agronomic metrics of plant height and leaf area index. At harvest, using calibrated scales, total weight of yield per zoned area was calculated.

Statistical Procedures

Statistical analysis was performed using appropriate software for all obtained data. Prior to testing the hypotheses, normality and homogeneity of variance were obtained. One factor analysis of variance was used to analyze the differences between irrigation treatments and Tukey's post hoc test was used. A probability value of less than 0.05 was considered as statistically significant.

Materials and Methods

System Deployment and Operational Stability

The plant-centric irrigation architecture operated continuously with no interruptions and no loss of data during the entire period of the experiments conducted. All sensor nodes sustained continuous Wi-Fi connections with the central gateway and no data packets were corrupted and no communication loss took place within the effective coverage range. Because of the duty cycle of the sensors during the experiments and the powering of the sensors with solar panels, the battery voltages were at levels that allowed them to operate, thus confirming the efficient design of the system during the experiments conducted in the field. All nodes were actively participating in the irrigation system to monitor and log data related to drought stress during the entire period of the experiments, and the gateway made autonomously decisions regarding the irrigation of the plants including the execution of the irrigation system. These results support the sustainability and practicality of the system architecture design on the field in agriculture (Figure 1).

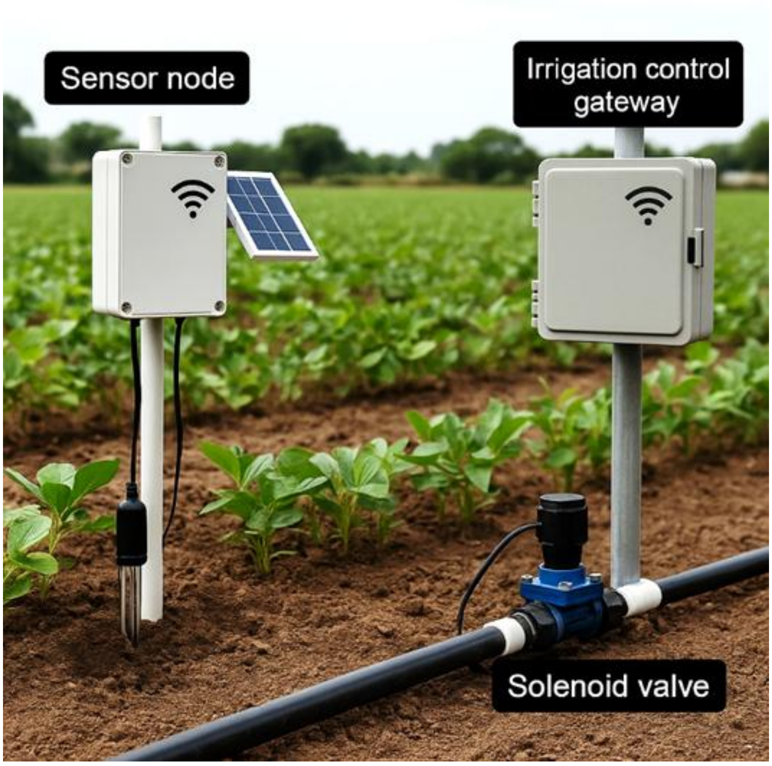

Figure 1. System architecture and field deployment

Variability of Drought Stress Indices Across Irrigation Methods

Significant variability in the patterns of drought stress indices was noted among the three groups of the irrigation methods. In the case of the manual irrigation group, drought stress indices exhibited significant variability with sustained elevated drought stress periods prior to relative to the periods of irrigation. In the case of the soil moisture-based irrigation group, the drought stress indices did demonstrate some level of partial stabilization; however, the periods of drought stress remained in elevated levels throughout periods of high evaporative demand. In the case of the proposed irrigation system, DSI values help study the synchronization of demand to the plant water DSI values demonstrated an improvement to coordination of demand water to irrigation frequencies relative to the moisture levels to the soil. Figure 2 illustrates the system.

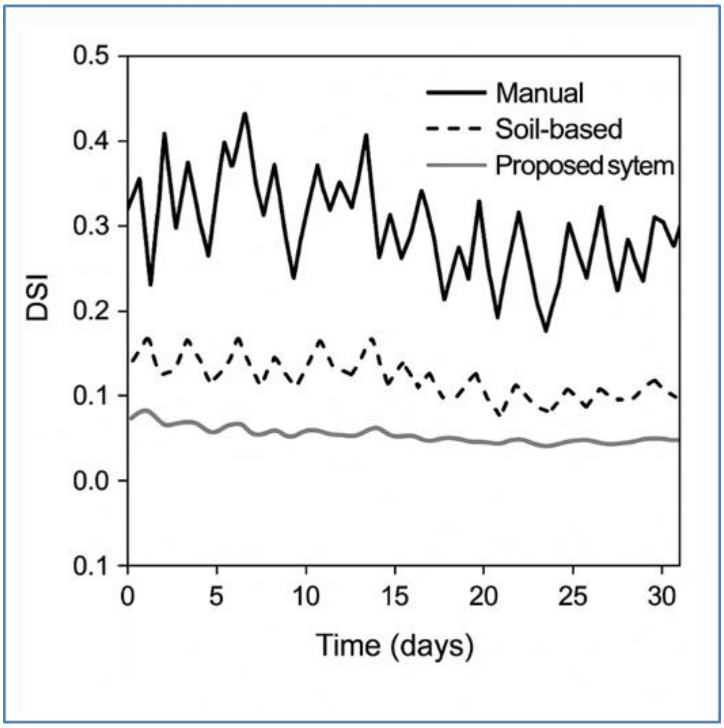

Figure 2. Temporal variation of drought stress index

Water Calculated to be Used in Total

There was a significant difference in total water used among the irrigation methods based on the practices of the irrigational moisture system. In manual irrigation methods, the total water utilization for irrigation was the highest which picked up the conservative practices of over irrigation. In the moisture-based system, the water conservation practices underwent a slight level of water conservation, with the moisture in the soil being adequate for the irrigation of the plants. In the plant-centered system, the total water was minimal which resulted in the manual irrigation 37% water total being reduced, while the conventional smart irrigation system demonstrated a 21% water conservation. In the irrigation methods from the surrounding practices of the irrigation, the statistical used demonstrated significant difference was 0.01 which pointed to irrigation. Architecture was the method of water for the bettering of the irrigation practices.

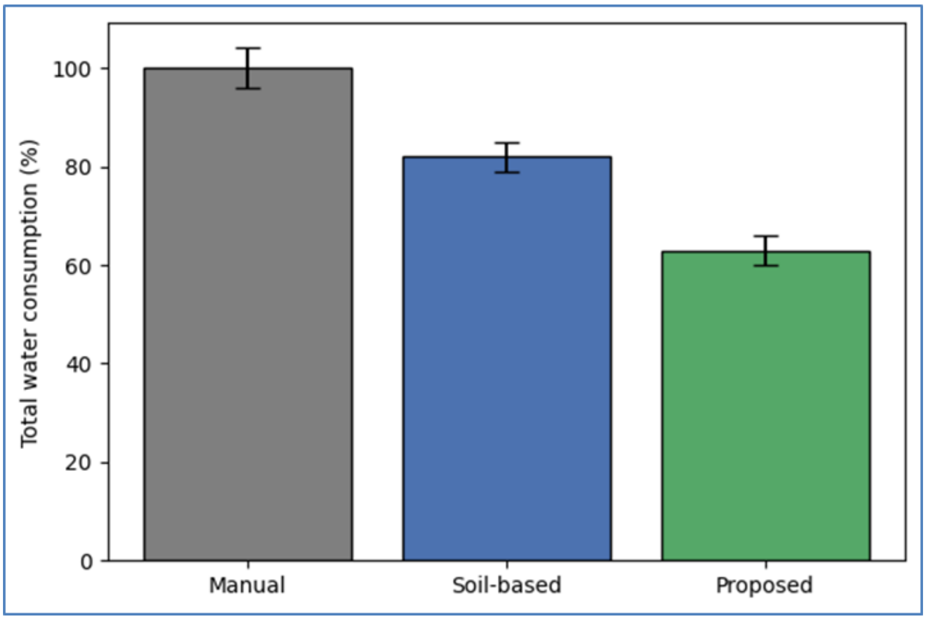

Figure 3. Total irrigation water consumption

Management of the Frequency and Duration of Irrigation

The system has optimally balanced the frequency and duration of irrigations by adaptive learning of the post-irrigation responses of the plants. Manual irrigations also had poor timing and duration had too much scope, and control based on soil moisture had too brief too frequent control of activations. The system, on the other hand, contrived longer intervals of relief from irrigation stress by reducing the frequency of irrigation activations and achieved greater water use efficiency per irrigation event. This overall adaptive response contributed to drought mitigation without stress to the plants. This contributed to water conservation irrigation cycles without plant stress. This is shown in Table 1.

Table 1. Irrigation frequency and duration

Treatment	Irrigation events (n)	Mean duration (min)	Total irrigation time (h)
Manual	28 ± 3	42 ± 5	19.6
Soil-based	34 ± 4	31 ± 4	17.6
Proposed system	**19 ± 2**	**28 ± 3**	**8.9**

The Performance of the Plant Growth

The measurements of the growth of plants show the advantages of the irrigation architecture. The plants, which had been irrigated by the created plant-centric system, achieved greater height, leaf area index, and more uniformity of the canopy than both of the control treatments. The soil moisture system also had moderate improvement over the control of manual irrigation. The system did show statistically significant differences and the created system was favored in the study. This supports the premise that where the timing of irrigation is optimally aligned with the plant physiological demand, a significant decrease in the volume of water retained in the system whilst a healthier greater vegetative growth is achieved. These relationships are shown in Figure 4.

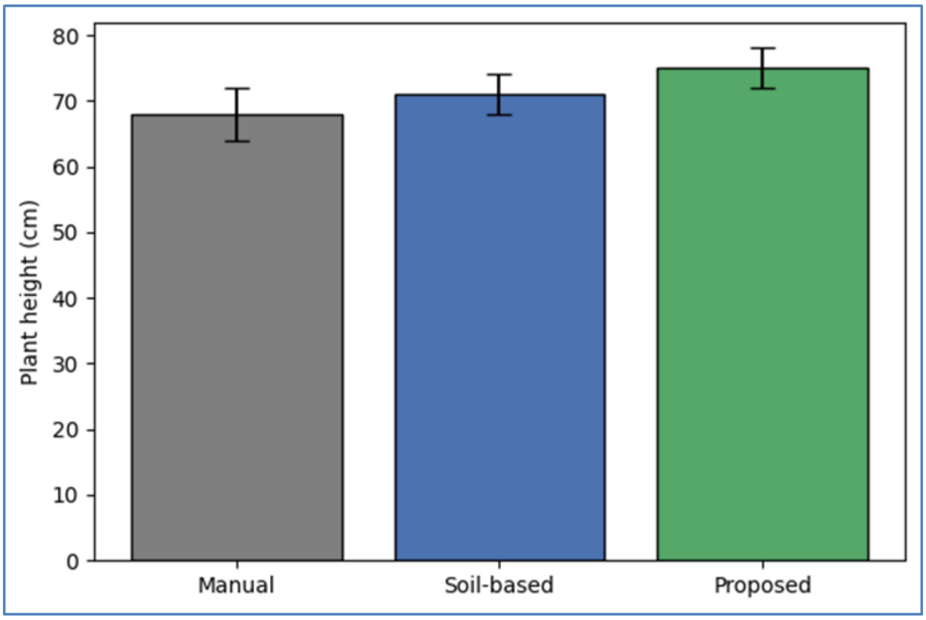

Figure 4. Plant height at harvest

Final Crop Yield

Ultimately, the yield analysis showed that the new system resulted in both water savings and productivity gains. The plant-centric irrigation treatment had the highest yield per unit area, followed by the soil-moisture-based system, while outdoing the yield of areas under manual irrigation. The yield improvements were the result of reduced drought stress exposure at critical growth stages. Statistically, there were significant differences in the yield observed between the irrigation system and manual irrigation ($P < 0.05$), confirming that the savings in irrigation water were accomplished without yield penalties (Figure 5).

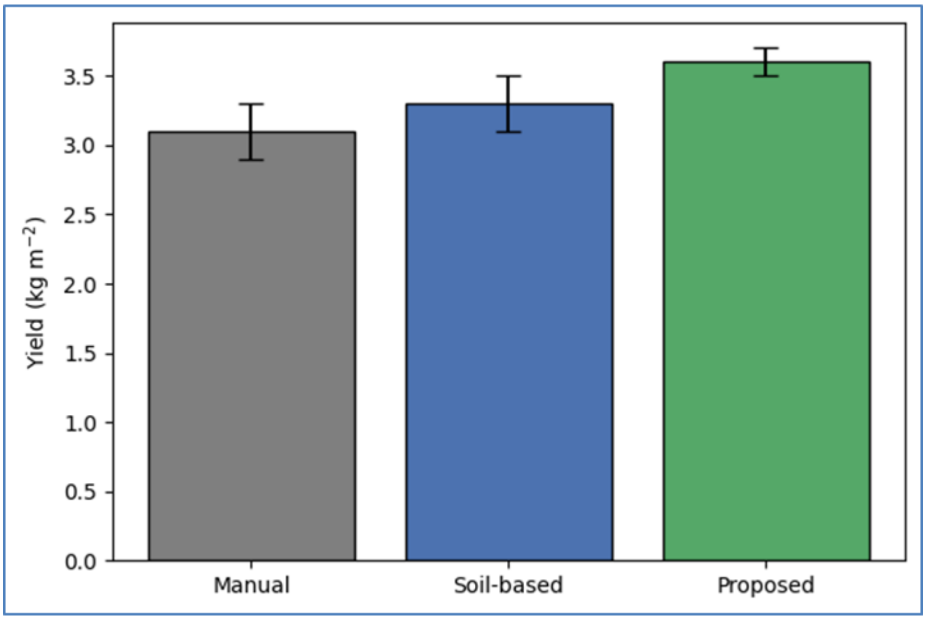

Figure 5. Final crop yield

Irrigation fault detection performance

The system has been able to correctly diagnose irrigation faults based on abnormal patterns of DSI responses. The system issued automated fault alerts when valves were opened, but DSI showed no drop within the expected periods. Inspection showed blocked emitters and lower than expected flow in the areas with alerts. Diagnostic capabilities of other irrigation systems, whether manual or soil-moisture based, were limited and did not provide comparable fault diagnosis. This, therefore, exceeds user expectations by adding an additional dimension of operational dependability and system reliability. (Figure 6).

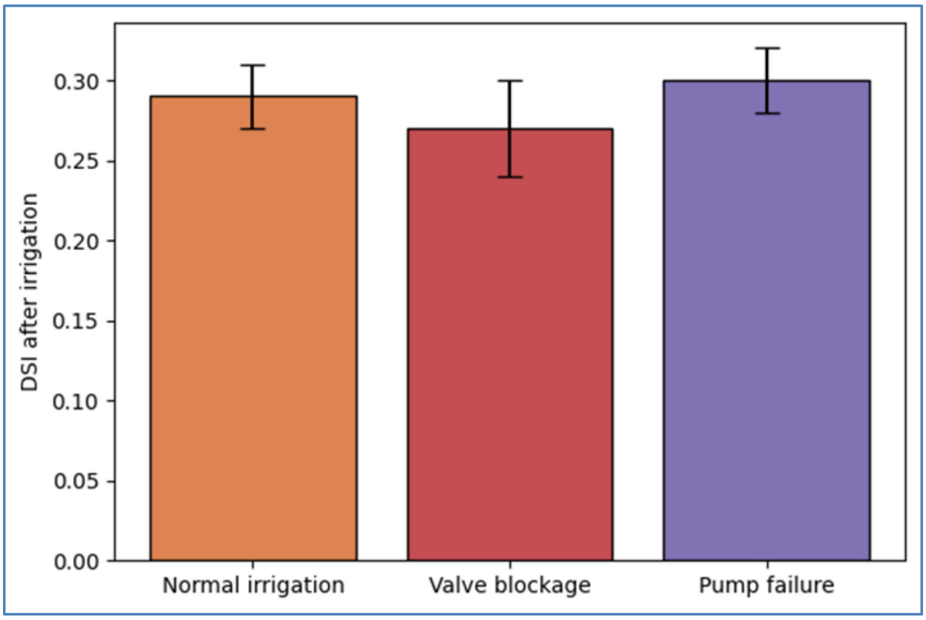

Figure 6. Irrigation fault detection based on DSI response

Statistical Summary of System Performance

An abstraction of the key performance metrics reaffirms the excellence of the structure. One-way ANOVA testified to the existence of significant treatment effects concerning the parameters of water usage, drought stress stability, and yield. The system was most frequently placed at the top of the hierarchy in the comparison of the post hoc treatments in terms of both efficiency and agronomic effectiveness. These results confirm, in conjunction, the technical, biological, and functional merits of the patent-oriented irrigation system (Table 2).

Discussion

The findings of this investigation indicate that soil moisture-based irrigation control strategies are not adequate to represent the true plant water status. This limitation has been discussed mostly in the recent irrigation literature where plant-based moisture indicators have been shown to signal water stress earlier and more reliably than soil moisture indicators [8–10]. Similarly, the proposed plant-based structure had and sustained significantly lower and more stable drought stress index (DSI) values as compared to manual irrigation and soil moisture-based irrigation. The smaller stress amplitude in this study suggests the combination of temperature and optical plant signal was effective in irrigation control, which resulted in closer alignment of irrigation events to plant water need, as also proposed by Brunetti et al. and Leme de Paulo et al. [11,12].

The projected irrigational systems have shown remarkable water savings and neither stunted crops nor yields. Improvements have also been noted in other irrigation systems that use crop water stress indices to regulate the systems via the internet (IoT) (2,6). Unfortunately, most of the other systems that have been reported rely on node and agent systems, which can be very energy hungry and limit the actual use of the systems (8,9). The current architecture, however, incorporates local control of low power Wi-Fi and on-location data processing to focus on energy-efficient systems that are in high demand and do not require constant internet connection (8,9). The reduction in the frequency of irrigation and the total water used demonstrates the effectiveness of systems that use learning from the active plant (responsive control) as opposed to systems that simply use predetermined static irrigation rules.

The study’s second main finding regarding the system’s monitoring capabilities is the sample system's ability to monitor DSI behavior and detect irrigation errors .The majority of literature in smart irrigation provides little to no attention to fault detection in the irrigation system and focuses almost exclusively on scheduling efficiency [11,12]. The ability to detect a fault on the system, especially a valve blockage or a pump failure, by monitoring the stress response of the plants is a crtical addition to the system’s irrigation management capabilities and improves the system’s preventive maintenance by eliminating the risks of undiscovered stress in the plants. This advancement also allows irrigation system on the market on the worldwide for irrigation wireless sensor networks [13, 14] to support a the system and infrastructure of smart agriculture with higher self-reliability and resilience.

Conclusion

The proposed design for a patent in a smart irrigation management system, with the ability to detect and monitor plant drought stress, as well as the ability to monitor and control Wi-Fi connected devices adaptively and autonomously, provides an means of Monitor and control adaptive and autonomously. The system provides efficient and effective management of irrigation systems. The system also provides means of managing control systems to be based on the plants, thereby reducing water usage. This is the key difference of the proposed systems in the market today. This proposed system has the ability to autonomously monitor and adapt to irrigation faults as well. This further increases the practical aspect of this design. The design proposed in this study is a scalable, energy efficient, and intelligent irrigation system. This system promotes sustainable water management in agriculture. The studies activities support the proposed architecture.

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