AATCC Review

24 August 2024: Received
26 September 2024: Revised
03 November 2024: Accepted
26 November 2024: Available Online

https://aatcc.peerjournals.net/

Review Article

Open Access

Irrigation scheduling based on intelligent strategies to enhance crop yield and water conservation: An in-depth analysis

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ABSTRACT

Agriculture being highest water consumer is responsible for two third of total withdrawals. The inspiration for this review study originated from developing countries particularly India where agriculture and climate conditions are crucial to the economy. In many parts of the India, irrigation water has been over-exploited, while freshwater shortage is becoming critical in the arid and semiarid areas. Profitability in production farming is dependent on making the proper and timely operational choice based on current conditions and previous records. Appropriate irrigation water management has gotten a lot of attention since it is critical to ensuring global water and food security. A smart irrigation system is used to make better use of water in agricultural fields and to increase crop productivity. As a result, the high demand for water resources is lessened, as are the negative environmental effects of irrigation. Various irrigation systems have been developed to reduce over-irrigation by evaluating soil moisture content or crop water stress index. The purpose of this study is to examine smart irrigation technologies and describe how they affect water savings, production, and crop quality. According to an examination of important studies, the water consumption efficiency based on soil moisture sensors is dependent on the volumetric moisture content threshold value chosen by farmers. Soil moisture sensor controllers, evapotranspiration controllers, and rain sensors have all been found to save 40%-50%, 30%-40%, and 7%-26% of water while preserving crop growth and quality, respectively. The IoT-based approach outperformed on-site measurements in terms of assessing crop and soil variability in the field.

Keywords: *Irrigation scheduling, intelligent strategies, water saving, soil moisture sensor (SMS), soil moisture content (SMC), depletion of available soil moisture (DASM), ET controller, rain sensor, and IoT*

Introduction

Human civilization is preparing for a population surge that will reach 10 billion people by 2050 [48]. To keep up with this expansion, global food production is expected to increase by at least 70% in the future years [47]. Farmers continue to utilize conventional strategies based on expectations of the crop's nutritional needs, despite the fact that agricultural practices have not advanced significantly over the years. Delivering the same nutrition input across the entire farm is no longer the best option since it results in excessive fertilizer and pesticide use, wasteful water consumption, environmental damage, and expensive operational expenses [10].

Global food consumption is increasing due to rapid population expansion, putting more strain on water resources [17]. Water is mostly consumed in agriculture, with irrigation accounting for over 70% of worldwide water withdrawals [45]. Water scarcity is one of the primary issues confronting the agriculture industry in arid and semi-arid climates [37]. This issue is raised because farmers provide regular irrigation to all portions of the crop field without addressing the crop's water requirements. A disadvantage of the aforementioned irrigation strategy is over or under-irrigation of particular parts of a farm, which may result in undesirable water stress on the crops [1]. Thus, appropriate irrigation water management is critical to ensuring global water security [37]. The gap between water demand and supply in agriculture is regarded as a problem that should be addressed by utilizing sophisticated technologies to maximize irrigation water use [39]. A smart irrigation system is a long-term water-saving approach for increasing crop productivity while minimizing the negative environmental effects of irrigation [27].

Regulated deficit irrigation (RDI) refers to an irrigation technique in which a crop is supplied with a quantity of water that is below the optimal requirement for plant growth. This practice aims to decrease water usage in irrigation, enhance plant response to a certain level of water scarcity positively, and either reduce the volume of irrigation water used or increase the Water Use Efficiency (WUE) of the crop. Stage-based deficit irrigation, a type of RDI, involves applying reduced water amounts at specific stages of plant growth, ensuring full plant evapotranspiration is met during critical growth phases while applying less water during non-critical stages. Successful implementation of this method requires determining the critical growth stages of a particular crop variety and assessing the crop's sensitivity to water shortage at different life cycle stages.

Partial root-zone irrigation is another commonly employed RDI technique, where half of the root system receives full irrigation while the other half is exposed to drying soil conditions. This method typically includes Alternate partial root-zone irrigation and Fixed partial root-zone irrigation.

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DOI: https://doi.org/10.21276/AATCCReview.2024.12.04.379

Positive impacts of partial root-zone irrigation have been observed in various crop species. Subsurface irrigation, the third popular RDI approach, delivers water to plants through capillary action from below, unlike traditional overhead irrigation where water saturates the soil's air spaces first. This infiltration process triggers plant adaptations such as enhanced tolerance to water stress through internal physiological adjustments. Subsurface irrigation is predominantly used in nursery settings and to a lesser extent in large-scale crop production. In recent years, research efforts have focused on understanding the mechanisms underlying RDI to reduce water use and improve WUE without compromising yield. Two key theoretical assumptions have been proposed: firstly, slight closure of stomata under RDI-induced water stress conditions may enhance leaf water retention without significantly affecting photosynthesis; secondly, when a portion of the root system experiences drying soil conditions in partial root-zone irrigation, it signals enzymatically to the shoots, prompting stomatal closure and activating drought-tolerant mechanisms. Common parameters studied include leaf water content, stomatal morphology, photosynthesis, and respiration.

Numerous studies have demonstrated that plants typically synthesize phytohormones in reaction to RDI. Of particular significance is the role of these phytohormones as signaling molecules, overseeing various biochemical mechanisms in plants and mitigating the potential harm induced by RDI-triggered water stress. Biosynthesis under RDI-induced water stress occurs indirectly through the generation of the organic pigment carotenoids in chloroplasts and chromoplasts. The catabolic pathways of abscisic acid may differ based on the intensity of the stress, as indicated by [6]. When facing mild water stress, abscisic acid might undergo catabolism through conjugation to yield abscisic acid glucose ester, whereas, during severe water stress, the oxidation pathway is favored, resulting in the creation of catabolites such as phaseic acid or dihydrophaseic acid. Moreover, the responses of antioxidant enzymes to water stress exhibit variability among plant species or cultivars, as noted by [40]. The sensitivity of enzymatic reactions is influenced by inherent genetic characteristics in plants.

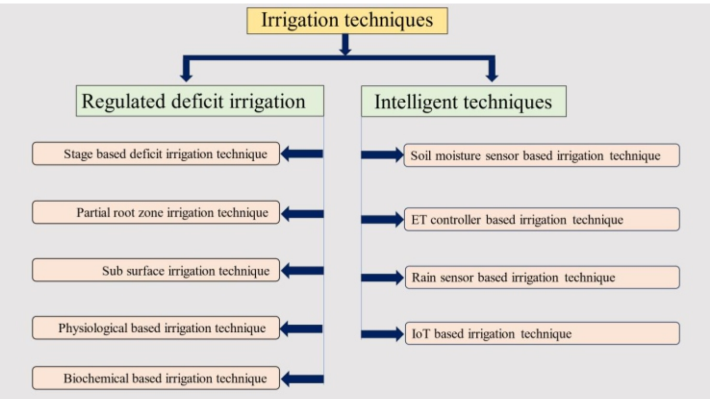

Figure 1: Intelligent and regulated deficit techniques used for scheduling irrigation

Besides this, Several smart irrigation scheduling approaches, including soil moisture sensor (SMS) controllers, evapotranspiration (ET) controllers, Rain sensors, and IoT-based, have been developed and tested on a wide scale by various researchers.

1.1 Soil moisture sensor-based irrigation scheduling

Irrigation scheduling entails the determination of the timing and quantity of water application to achieve specific management objectives, typically aimed at avoiding crop water stress that could limit yields. Factors influencing irrigation scheduling encompass the crop type, growth stage, soil characteristics, soil-water interactions, water supply availability, and meteorological conditions (e.g., temperature, wind, precipitation) [52]. Efficient irrigation scheduling facilitates the maximization of profits while reducing resource inputs like water and energy expenses. Various approaches have been devised and utilized in the past to enhance irrigation scheduling, relying on the monitoring of factors such as crop water consumption, soil moisture status, and crop canopy temperature. Among these methodologies, the monitoring of soil moisture has been a subject of research and application for many years. Despite this extensive history, the integration of soil moisture sensors for precise irrigation scheduling has been somewhat constrained. Soil moisture sensors serve as crucial instruments that aid farmers in optimizing irrigation practices, safeguarding water reservoirs, and sustaining profitable crop yields. They offer valuable insights into field conditions, enabling better utilization of land, time, and resources.

These sensors may be either stationary or portable, such as handheld probes. Stationary sensors are positioned at predetermined spots and depths within the field, whereas portable soil moisture probes can assess soil moisture levels at multiple locations. Soil moisture sensors are categorized based on the technology utilized into two groups: (1) Devices measuring volumetric water content and (2) Instruments gauging soil tension when positioned within the soil profile. To comprehend the operation of these devices, it is imperative to grasp the concept they are assessing, namely Volumetric Water Content (VWC). VWC quantifies the water content within a soil volume, represented as a percentage of the total volume. Soil water tension signifies the energy demanded by plant roots to draw water from soil particles. As water is extracted from the soil, the soil tension escalates. Soil tension is typically measured in centibars (cb) or bars of atmospheric pressure. When the soil is saturated with water, the soil water tension approaches zero. In soils with coarse textures, Available Water Capacity (AWC) reaches 50% depletion at soil tension levels of 25-45 cb. For such soils, irrigation should be conducted prior to the sensor indicating 25-45 CB. In the majority of cases, crops typically initiate stress conditions upon reaching a soil water depletion/deficit of 30-50% of the available water holding capacity (AWC). This threshold is known as the management allowable depletion (MAD) or irrigation trigger point. The MAD value is subject to fluctuations based on the specific crop type, growth phase, and the pumping capacity of the irrigation system. It is advisable to commence irrigation activities when the percentage of soil water depletion aligns closely with or equals the percentage of MAD. The precision of the sensor holds significant importance, particularly in applications like precision irrigation, where even slight variations in moisture levels can greatly influence plant growth. It is advisable to seek sensors characterized by high precision and minimal measurement discrepancies. Soil moisture sensors are commonly deployed in challenging outdoor settings, exposed to severe weather conditions. It is recommended to opt for sensors that are robust, enduring, and capable of enduring exposure to moisture, heat, and cold. Variations exist in the output of sensors across different models, necessitating careful consideration of output type and compatibility with data loggers and other devices. Some sensors furnish analog or digital outputs, while others transmit data wirelessly.

The cost factor of the sensor bears significance, especially in the context of large-scale setups. It is advisable to select sensors that offer cost-effectiveness and long-term affordability.

Soil moisture sensors play a vital role in assessing water availability within the root zone of crops, enabling users to steer clear of both under-irrigation and over-irrigation, both of which can adversely affect farm profitability and sustainability. When integrating soil moisture-sensing systems into irrigation decision-making processes, several crucial factors demand attention: (1) The choice between point sensors and probes. Probes are typically easier to install and offer a more comprehensive insight into water availability along their length. (2) Sensor precision, particularly crucial in fields with high clay content or salinity levels. (3) Quality and positioning of installation, necessitating a gap-free, representative location that does not obstruct farm machinery or irrigation systems. (4) The method of accessing collected soil moisture data (wireless or manual) and the associated cost and convenience of each option. Able to efficiently and promptly translate collected data into irrigation decisions is also a key consideration. In general, SMS estimates and provides soil moisture content (SMC) data that a controller can adjust to a certain threshold. As a result, watering events will be skipped automatically when the SMC reaches the predefined level [28].

In the USA, researchers selected a large field and divided it into two parts in which one sensor node station was installed on the north side and the other on the south side of the field to capture the soil water dynamics and crop canopy status for soybean, and maize, respectively. The field was irrigated with a center pivot. The sensor-based decision support system (DSS) treatment witnessed higher irrigation water use efficiency (IWUE) for both maize and soybean with no significant difference in crop yield as compared to conventional irrigation treatments [46].

Chaithra and her co-workers use SMI prepared by Sugarcane Breeding Institute which senses the soil moisture and guides irrigation scheduling based on different colored light for example blue colored light indicates ample moisture and no need for irrigation while yellow light indicates low moisture and irrigation is advisable. Asensor-based drip irrigation at 25% DASM (depletion of available soil moisture) recorded significantly higher value of growth parameters, kernel yield, and stover yield of maize which remained at par with Green Soil Moisture Indicator (GSMI) based drip irrigation. The same treatment also recorded higher water use efficiency [12]. The SMS (Soil moisture sensor) based irrigation scheduling treatments reduced annual water use by an average of 66.2% as compared to control. All treatments exhibited similar turfgrass quality and remained above the minimum level of acceptable quality [43]. Similarly, the real-time soil moisture-based irrigation at the soil matric potential threshold level of –30 kPa with 120% of RDF through fertigation was recommended for attaining maximum green pea pod yield and water-use efficiency under semi-arid *Inceptisols* [4].

In the USA, Grower-controlled rows irrigated by timed cyclic irrigation events were scheduled by the grower for dogwood trees. Sensor-controlled rows were irrigated for a specified amount of time when the average volumetric water content (VWC) reading of sensors dropped below 46.0%. The weekly average irrigation applications to the sensor-controlled dogwood trees were 1.4 to 6.5 times less as compared to the grower-controlled trees, resulting in a reduction in irrigation water applications by up to 63% without reducing the growth or quality of the trees [9].

Similarly, the use of the sensor-based system to irrigate woody ornamental plant (*Pieris japonica*, *Hydrangea quercifolia,* and *Kalmia latifolia* species) production, resulted in an approximate 50% reduction in irrigation application (volume) when compared to grower-managed irrigation with no similar growth and equivalent or slightly reduced crop losses as compared to grower-managed [50].

The sensor-based drip irrigation (DI) provided 15% higher fruit yield of banana with 20% water saving, resulting in 40% higher water productivity as well as ensured better fruit qualities (total soluble solids and acidity) as compared with manually operated DI [38]. A wireless SMS was installed in a 0-100-cm soil profile in an autonomous drip irrigation system in a greenhouse tomato cultivation experiment. The spatiotemporal characteristics of soil moisture distributions were used in this system to approximate dynamic plant water absorption depth, and the estimated data were collected utilizing a central irrigation regulator to achieve an exact irrigation depth at each irrigation scheme. The tomato irrigation water consumption efficiency reached 41.23 kg/m3, a significant improvement above that obtained using a traditional irrigation system (31.58 kg/m3) [25]. A significantly higher tomato fruit yield as well as maximum water use efficiency and -benefit-cost ratio recorded in treatment soil moisture sensor-based drip irrigation over other treatments [36].

The sensor-based irrigation scheduling (S-BIS) and time-based irrigation scheduling (T-BIS) reduced the applied irrigation water amount by 64.1% and 61.2%, respectively when compared with traditional surface irrigation (TSI) for date palms. Significantly highest values of marketable yield and water productivity were noted at the controlled subsurface irrigation system (CSIS) with the S-BIS method [31]. Besides this, significantly higher okra yield and maximum water use efficiency were recorded in treatment 100 % FC, based on soil moisture sensor under ADI with 100 % RDF through fertigation in equal splits at 4-day intervals than other irrigation based treatments [44].

In the mustard field, a fuzzy system was adopted in which an aggregator collects the data from sensors in the field and passes it to the sensor node followed by the coordinator node which ultimately passes it to the central controller. After getting data from the sensor, fuzzy logic was run to decide the irrigation schedule. In the fuzzification process, the CWSI and soil moisture content are converted to fuzzy logic. The fuzzy inference is designed using the knowledge base to evaluate the fuzzy rules and produce an output for each rule. The 25 rules have been defined for the output variable. The output membership function is classified into five types, namely, zero (Z), low (L), medium (M), high (H), and very high (VH). Some interpretations of the rules are provided as follows: if CWSI is high (H) and soil moisture content is low (L), the pump is operated at 75% in high (H). A result showed that the implementation of the fuzzy system decreased water use by 59.61% and electrical energy consumption by 67.35%, while the mustard crop yield increased by 22.58% compared to the conventional system [21].

1.2 ET controller-based irrigation scheduling

Evapotranspiration (ET) refers to the combined process of surface evaporation and plant canopy transpiration, as defined by [3]. It plays a crucial role in the energy balance by trading energy for water release at the plant surface. The fundamental factors influencing ET include solar radiation, air temperature, relative humidity, and wind speed, as outlined by [5].

Reference ET (ETo) represents the evapotranspiration from an imaginary reference crop that mimics a vigorously growing, well-hydrated, dense green grass of uniform height, according to [5].

Evapotranspiration-based controllers, commonly known as ET controllers, are devices used in irrigation management that rely on ET estimations to schedule watering activities. ET controllers are controllers that use weather information to estimate ET [30]. These controllers vary in operation based on the manufacturer, typically incorporating landscape-specific settings to enhance efficiency, as suggested by [42]. The ETo data is received by ET controllers through three primary methods, leading to the categorization of ET controllers into three main types: standalone controllers, signal-based controllers, and historical-based controllers. Standalone controllers gather climatic information from local sensors and utilize algorithms to compute ETo, while signal-based controllers obtain ETo data from external weather stations. On the other hand, historical-based controllers utilize past ETo data to adjust irrigation schedules based on general climate trends, albeit less effectively due to the lack of real-time weather changes consideration.

While the utilization of evapotranspiration-based or ET-based scheduling has significantly progressed in enhancing water usage efficiency for irrigation purposes in recent years, there remains a necessity to refine the ET estimation techniques in regions characterized by diverse microclimates and mixed vegetation or inadequate fetch for conventional ET measurement approaches. In recent decades, the main ET controllers used for irrigation management have been stand-alone or manually programmed irrigation controllers, historical-based controllers that provide historical weather data, and signal-based controllers that estimate real-time weather data received by on-site systems [29].

Apart from monitoring irrigation with SMS, ET estimates have also been used to schedule irrigation and are seen as a possible water-saving method [49]. This technique ideally offers irrigation based on the crop's ET requirements. Crop evapotranspiration (ETc) is the amount of water evaporated from the soil surface and transpired through the plant canopies. ETc is calculated as the product of ET_0 and the crop coefficient (Kc), which varies depending on crop type, production environment, and growth stage [14]. The amount of water required to replace ET is known as the crop water requirement (CWR). Weather characteristics (such as temperature, relative humidity, and wind speed), crop factors (such as crop type), and management and environmental factors (such as soil fertility) can all have an impact on a crop's water need (ETcrop) [23].

A trunk diameter, plant height, mean fruit number, and mean fruit weight of papaya fruit for the sensor-based set schedule treatment were significantly lower as compared to historic ET and schedule irrigation for soil water sensor-based treatments which received only about 31–36% of the water applied in the set papaya crop [29].

At Kingdom of Saudi Arabia, investigated two types of evapotranspiration-based smart irrigation controllers, SmartLine and Hunter Pro-C2, as promising tools for scheduling irrigation and quantifying plants' water requirements of tomato crops. The conventional irrigation scheduling method was kept as a control treatment. The soil water status was measured by the Tensiometer, WaterMark, and EnviroSCAN devices in the SDI plots under the SmartLine, Hunter, and control treatments. A significantly highest vegetative growth characteristics, fruit yield of tomato, and water irrigation efficiency for the smart irrigation controller (Hunter) as compared to the control [2].

A smart system that is connected to an ET module that can sense the local climatic conditions via different sensors that measure wind speed, rainfall, solar radiation, air temperature, and relative humidity. The ET module then receives data from the ET sensor and applies it to the individual fields (zones) of irrigation. The IIS automatically calculates crop evapotranspiration (ETc) for local microclimates and takes a decision to initiate irrigation by opening the solenoid valve and pump. In the control treatment, the climatic data are gathered from a weather station, and the daily reference evapotranspiration rate (ETo) is calculated and utilized in making irrigation decisions through manual calculation. A higher water use efficiency under intelligent irrigation scheduling (IIS) showing 31% and 26% water saving as compared to the irrigation control system (ICS) while significantly improving growth parameters and yield of tomato crop [30].

The maximum yield, saving of irrigation water, and increased water use efficiency of tomato crops were found with the application of irrigation using an ET controller sensor as compared to a watermark sensor and control treatment [18]. Similarly, the sensor-based irrigation system was superior to the conventional irrigation system in terms of plant height, number of branches, fruit length, fruit diameter, average fruit weight, total yield, water use efficiency, and irrigation water use efficiency during both seasons for tomato crop [19].

A similar method was utilized for strawberry irrigation management, with a 10-year series of recorded ET0 being used. The water requirements were then updated using data from the weather station and SMS [32]. Deficits in water supply were detected in a simulation study conducted using Root Zone Water Quality Model-based software [20], and 4-day-ahead weather forecast data (precipitation, air temperature, humidity, wind speed, and radiation) were developed for soybean and corn irrigation management by simulating the appearance of water stress and then determining the volume of irrigated water to be supplied to return the current soil water content to the soil. This type has a water-saving capacity of up to 35% without impacting crop output.

Moreover, irrigation at or below −30 kPa during the initial phase (<90 DAS) and at −15 kPa during the remaining period produced a comparable yield of direct seeded rice (DSR) with significantly higher irrigation water productivity (0.24 kg/m^3). Whereas, transplanted puddle rice (TPR) registered lower IWP (0.18 kg/m^3) as compared to the best DSR treatment but recorded about 11% higher grain yield with significantly higher crop water productivity (0.58 kg/m3) than DSR [24].

1.3 Rain sensor-based irrigation scheduling

The Rain Sensor represents a specialized sector within the landscape and agriculture industry, focusing on the creation and dissemination of rain sensors tailored for irrigation systems. These sensors are essential elements in automated irrigation systems, detecting rain and instructing the system to pause watering temporarily. The primary role of an irrigation rain sensor is to save water by preventing unnecessary irrigation during and after rain, promoting water efficiency in landscaping and agricultural uses. The market resonates with the increasing emphasis on sustainable water management practices and effective irrigation solutions.

Opportunities in the Irrigation Rain Sensor sector are steered by the rising consciousness of water conservation, environmental sustainability, and the demand for intelligent irrigation technologies.

As societies, enterprises, and agricultural activities aim to optimize water consumption, possibilities emerge for innovative rain sensors with advanced functionalities like wireless connectivity, adjustable sensitivity, and compatibility with smart irrigation controllers. Moreover, the market gains from the expanding uptake of automated irrigation systems in residential and commercial environments, where rain sensors hold a crucial role in augmenting the efficiency and resource utilization of these systems. Market segmentation could entail classifying rain sensors based on their technologies, such as wired or wireless, and their uses, encompassing residential lawns, commercial landscapes, and agricultural fields. Further categorization might take into account sensor types, differentiating between tipping bucket sensors, capacitance sensors, and optical sensors, offering choices that cater to the varied requirements and preferences of users across diverse irrigation settings. Providing a variety of rain sensor solutions enables the market to meet the specific needs of different users, contributing to the overall progress of water-efficient irrigation practices.

Despite not being classified as smart technology, rain sensors disrupt the irrigation process during rain events when watering is unnecessary. Watering in the rain leads to water and financial waste, as well as unnecessary runoff. There are three distinct types of rain sensors available, each operating based on distinct principles. The traditional rain sensor currently in operation functions by utilizing a small cup or basin to accumulate water, at which point a predetermined volume causes a disruption in the irrigation process due to the cup's weight. The presence of debris inside the cup may also lead to an interruption in the irrigation cycle, necessitating periodic inspection and removal of any litter. A different kind of rain sensor employs a dish with two electrodes positioned at a specific distance above the cup's bottom. This distance is adjustable to accommodate light rain events. Similar to the initial rain sensor type, the accuracy of this system can be compromised by debris displacing water in the cup. The irrigation cycle is halted once the water reaches the electrodes. In contrast, the third category of rain sensors eliminates the need for a rain catch cup, resulting in a system that is both reliable and requires minimal maintenance. Instead, this sensor utilizes multiple expanding disks that activate the switch when wet. Once the disks dry out, the system will resume its scheduled cycles. It is advisable to inspect the disks annually to assess the need for replacement. All devices should be installed in an exposed location to receive rainfall.

The potential water conservation achieved is contingent upon the annual precipitation levels. In years with average to above-average rainfall, water conservation is more substantial compared to dry years. While rain sensors have demonstrated payback periods of less than a year, continuous monitoring is essential for optimal performance [11]. For instance, if a homeowner's irrigation system covers a ¼-acre yard and dispenses 1 inch of water per cycle, each cycle delivers 6,789 gallons of water. At a cost of $5.00 per 1,000 gallons, the savings amount to $33.95 whenever the irrigation cycle is interrupted by rainfall. Considering each rainfall occurrence, significant water and cost savings can be anticipated by the homeowner. Wireless rain sensors tend to be pricier, ranging from $120 to $200, while wired counterparts cost around $30 to $50.

RS is intended to suspend scheduled irrigation events after a certain depth of rainfall has occurred. The rain sensor detects the amount of rain that falls in an agricultural field. Based on the current conduction caused in the detector module, the amount of rainfall is determined. The module has four supply lines at various levels, as well as one ground line, which is utilized to determine the various water levels in the rain detector. The rain detector's working voltage is 5 V DC. [8].

The impact of Mini-Clik RS (Hunter Industries, Inc., San Marcos, CA) on water savings and turf quality studies at two rainfall set points (3 mm and 6 mm) and three different irrigation frequencies (1, 2, and 7 days/week) revealed that RS with different set points and irrigation frequencies had water savings ranging from 7% to 30% with acceptable turfgrass quality [28].

To assess real-time rainfall, RS was connected to an ARM7 microprocessor (Shenzhen Leadwon Electronic Technology Co., Ltd. China), and the SMS determined the amount of water existing in the soil based on the rainfall information of the land. The sensor data was used to monitor the irrigation pump motor, which was subsequently communicated to the farmer's smartphone via GSM (Global System for Mobile Communications) technologies. When compared to drip irrigation, the water-saving results of the method evaluated on tomato growing were up to 50% in the germination stage and more than 30% in the repining periods [8]. The same smart irrigation system was used to monitor paddy irrigation, and it was discovered that 41.5% and 13% of water may be saved, respectively, when compared to the conventional flood and drip irrigation procedures [7].

Control is an irrigation plan without a sensor (control) programmed to apply 0.5 inches of water twice a week in the United States. Rain sensor-based irrigation is used in treatments 2 and 3. There were two types of rain sensors used: rainbird sensors and Hunter rain sensors. Both are connected devices with a rainfall threshold that may be adjusted by the user. Each was linked to its own timer for outdoor irrigation. RS was put 10 feet above the ground. Rain sensor (RS) treatments reduced annual water use by an average of 22.1 as compared to control. All treatments exhibited similar turfgrass quality and remained above the minimum level of acceptable quality. Under these experimental conditions, the average Return on Investment for RS in the first year of installation was predicted to be $87 [43].

Another study compared the water-saving potential of two RS kinds (Mini-Clik and wireless Rain-Clik), with the wireless Rain-Clik accounting for the highest potential water conservation of 44% [11]. Similarly, at 32-mm irrigation depth and 2-days/week irrigation frequency, RS-based Bahia grass irrigation systems save up to 49% more water than traditional irrigation. RS was also used to regulate the leachate NO3-N and NH4-N [15].

1.4 IoT-based irrigation scheduling

An IoT-based intelligent irrigation system has been introduced, utilizing IoT applications to enhance agricultural productivity. The system incorporates soil moisture sensors to monitor soil parameters such as moisture content, pH, and humidity, as well as to track crop nutrition and weather conditions. Data collected by a microprocessor is transmitted to the user's mobile device using a GSM module to establish a communication link. By employing real-time soil data, the system controls a pumping motor through an operational amplifier, activating it based on soil moisture levels. Through IoT connectivity, farmers can access soil moisture information via a mobile application or web interface, including details on water sprinkler status. The system consists of a sensor hub and a control hub, providing valuable insights for multi-crop systems. This technology reduces manual labor in irrigation, enhancing efficiency and productivity, which is particularly advantageous in regions with scarce rainfall. By employing various sensors and actuators, an IoT-based irrigation monitoring and control system autonomously delivers optimal water levels from a reservoir to crops, illustrating the potential for efficient and automated irrigation management. The goal of the system is to boost agricultural productivity through autonomous monitoring and operation of remote farms. By utilizing a soil moisture sensor, a pump, and a Wi-Fi module, the system gathers real-time data and transmits it to a web server, enabling users to monitor soil moisture levels for precise irrigation control. The system's adaptability and cost-effectiveness are reinforced by experimental and simulation findings, highlighting the advantages of remote monitoring and control for irrigation systems.

An IoT-based smart irrigation system provides a multitude of advantages compared to conventional irrigation techniques. IoT-driven smart irrigation systems have the capability to gather information on soil moisture levels, weather patterns, and plant requirements, enabling precise watering based on actual necessity rather than predetermined timetables, thus aiding in water conservation and waste reduction. Accurately timing watering activities based on real-time data can lead to a decrease in energy consumption related to water pumps and sprinkler systems within smart irrigation systems. The implementation of a smart irrigation system eliminates the necessity for manual adjustments or monitoring of the irrigation timetable, thereby allowing gardeners and farmers to allocate time to other responsibilities. Over-watering can result in heightened humidity and moisture levels, fostering the growth of pathogenic microorganisms; smart irrigation systems can prevent such circumstances by adapting to the plants' actual requirements. Remote control and monitoring of irrigation systems through smartphones, tablets, or computers are facilitated to users, enabling convenient management even in their absence from gardens or farms. Smart irrigation systems can be synchronized with weather APIs to modify watering schedules based on prevailing weather conditions like precipitation, temperature, and humidity. The amassed data from smart irrigation systems can be scrutinized over time to enhance water usage efficiency, boost crop well-being, and anticipate future requirements. By supplying plants with the appropriate amount of water according to their distinct needs, smart irrigation systems can foster healthier and more vigorous plant development; this precise watering can mitigate the risks of overwatering or underwatering, which may induce plant stress and diseases. Although the initial investment in a smart irrigation system may surpass that of traditional systems, the long-term savings from decreased water and energy consumption often compensate for this expenditure. Through the minimization of waste and optimization of water utilization, smart irrigation systems play a role in conserving water resources and lessening environmental impact. In conclusion, the incorporation of IoT technology into irrigation systems presents a sustainable and effective approach to water resource management for agriculture and horticulture, offering ecological, financial, and societal advantages.

IoT is defined as a network of autonomous objects that connect and share data remotely via the Internet [26]. The supply-demand mismatch is widening, creating new issues and putting strain on the agricultural supply chain [16]. The Internet of Things (IoT), a concept that connects wireless and mobile tools incorporated via the Internet [33], is important in many areas, particularly agriculture [41]. Combining the IoT with the aforementioned sensors and connecting them to data platforms to offer real-time data and make more informed judgments enables intelligent irrigation solutions [34]. As a result, the Internet of Things facilitates crop irrigation operations in which water supplies may be regulated and monitored to fulfill demand while minimizing waste and operational expenses.

An irrigation system was installed in four motes connected to soil moisture sensors in the brinjal crop field. A gateway connected these sensors wirelessly. Other sensors, such as temperature, humidity, and wind speed, as well as the pump motor, are put in the field and are directly connected to the gateway. The microcontroller in the gateway monitored soil moisture 4 times a day. The gateway senses other climatic values when soil moisture falls below the permanent wilting point, and sends the sensed values to the server where CWR is computed; the motor is operated by the gateway for a pre-computed time duration based on CWR. About 53% of the water was saved from wastage when IoT-based crop field monitoring and irrigation systems were used to irrigate brinjal crops for 6 months [22].

Sensors of many types, such as optical, thermal, and multispectral sensors, can be included in UAVs [35]. In water-saving irrigation, for example, a UAV equipped with an RGB camera acquired photos of rice fields and correctly evaluated the height of rice plants using a strong correlation coefficient [51]. A six-band multispectral camera fitted on a multirotor UAV was recently employed in a semi-arid area to record photos at 50 m above the ground during cotton flowering and boll formation to monitor and calculate plant water content. 13 vegetation indicators were recovered from the camera in this experiment, and the findings showed that crop water content may be retrieved by combining crop canopy temperature with UAV multispectral data [13].

An irrigation system based on smart sensors which consist of ARM microcontrollers, smartphones, GSM modules, sensor units, and motor control units. The sensor unit comprises of temperature sensor, humidity sensor, light sensor, and rain sensor which is used to monitor the environmental conditions of the field. An irrigation application is developed for determining the wetness of the soil from the captured image and it is installed in the smartphone which is kept in a closed chamber having Transparent Anti - Reflective Glass (TARG) medium on one side of the chamber. The Global System for Mobile Communication (GSM) module in the proposed irrigation system is used for sending and receiving messages between the microcontroller and smartphone. Based on the data received from various sensors, the ARM microcontroller manages the irrigation by controlling the motor unit and periodically updates the information to the farmer. From the histogram, the system decides that the soil is wet and doesn't need to irrigate when the total numbers of pixels present in the grayscale image exceed 5000 at pixel intensity in and around 200. Otherwise, the soil is dry and responds according to the values received from the sensors integrated with the system. Based on the wetness of the soil and the rain sensor input, the ARM microcontroller operates the motor through the motor control unit. This system recorded that the soil image-based automation of the drip irrigation system consumes only 58.57% and 86.97% of water compared to the flood and drip irrigation, respectively. The proposed irrigation system saves nearly 41.43% and 13.03% of water as compared to flood and drip irrigation [7].

In another study, the comprehensive framework of the system, illustrates the system input coming through the deployed IoT device in the farm (soil moisture, temperature, humidity), satellite data (wind speed and direction), and predefined data (crop type, soil type, location, plantation date). The device was placed in a plastic box under the solar panel for protection from harsh weather conditions as the temperature peaked at 52 ∘C in the summer. The collected data are presented to the Decision Support System which recommends the irrigation scheduling for the farm. Control treatment was irrigated as a traditional estimation made by the farmers whereas IoT-based irrigation plots were irrigated using the recommendations made by the agriculture DSS. It was noticed impressive water savings (50%) combined with increased yield (35%) of lemon in IoT-based irrigation systems as compared with traditional irrigation scheduling under harsh environmental conditions where sometimes temperatures exceed 50 ∘C[53].

Conclusion

Irrigation techniques based on soil moisture sensors (SMS) work on a volumetric moisture content threshold value selected by the user. SMS controllers can reduce up to 40-50% of water consumption. ET controllers have been found to save up to 30-40% of water, and their performance is determined by the accuracy of ET0 calculations. A rain sensor can save up to 26% of water. In high water-demanding paddy crops, smartphone-based soil image processing techniques for determining soil moisture conditions can save up to 18% of water. An IoT-based system with several sensors and a decision support system was shown to cut water usage by 50% and 64% in lemon and date palm crops, respectively, while preserving production. Fuzzy logic-based irrigation scheduling was discovered to be a viable strategy for minimizing water consumption and increasing crop production in the mustard crop. Overall, sensor-based smart irrigation management solutions will minimize water usage, enhance water efficiency without sacrificing crop output, and can be used for field, nursery, and ornamental crops.

The future scope of the study

Future research should focus on the application of smart irrigation technologies in expanding types of consumable crops such as tomatoes, potatoes, and main cereal crops. Further research is needed related to the evaluation of the economic viability of the irrigation techniques studied. Farmers are becoming more aware of smart tactics and sensor availability in the market, as well as the usage of mobile applications, through agriculture agency and training centers.

Conflict of interest: The authors declare no conflict of interest.

Acknowledgment: I am thankful to Anand Agricultural University for providing all infrastructural facilities.

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