International Journal of Plant & Soil Science

Volume 36, Issue 9, Page 334-343, 2024; Article no.IJPSS.122362
ISSN: 2320-7035

A Comprehensive Review of Irrigation Systems Utilizing Sensor Technology

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2024/v36i94983

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/122362

Review Article

Received: 24/06/2024
Accepted: 29/08/2024
Published: 05/09/2024

ABSTRACT

The increasing need for water has become a significant cause for worry regarding the future of irrigated agriculture in numerous regions of the country. Hence, understanding the water requirements of crops is a crucial practical aspect for enhancing water utilization efficiency in irrigation methods. Conventional irrigation systems result in uneven water distribution, with certain sections of a field receiving excessive irrigation and others facing insufficient water supply. Given the evolving environmental conditions and water scarcity, there is a demand for a more effective system to manage field irrigation efficiently. The objective of this paper is to examine the necessity

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Cite as: *Kotadiya, R. H., P. M. Parmar, T. C. Poonia, D. J. Patel, and K. A. Kacchiyapatel. 2024. "A Comprehensive Review of Irrigation Systems Utilizing Sensor Technology". International Journal of Plant & Soil Science 36 (9):334-43. https://doi.org/10.9734/ijpss/2024/v36i94983.*

for soil moisture sensors in irrigation, explore sensor technology and assess their applications in various facets of agriculture and irrigation scheduling.

Keywords: Water demand; irrigated agriculture; water utilization efficiency; soil moisture sensors.

1. INTRODUCTION

Water is essential for photosynthesis and plant nutrition, with agriculture being the primary consumer of freshwater, utilizing 70% of the total fresh water, equivalent to 1,500 billion m^3 out of the annual 2,500 billion m^3. An important challenge in agriculture is the suboptimal utilization of water resources. India's greatest water consumer today is agriculture; in order to maintain the nation's self-sufficiency, consumption must be decreased, water resource management must be improved, and food crop output must rise by 60–70% by the middle of the century [1]. Since we are unable to fully utilize agricultural resources in a nation like India, where the economy is mostly dependent on agriculture and the climate is isotropic, we have introduced the automated irrigation system [2]. It is imperative that appropriate and effective irrigation water management and use methods be implemented in order to guarantee both financial and environmental gains.

Approximately 40% of the freshwater employed in agriculture in developing nations is wasted, whether through evaporation, spills, or absorption into the deeper layers of the soil beyond the reach of plant roots [3]. The issue of managing water in agriculture is now widely acknowledged as a significant challenge often associated with development concerns. Numerous freshwater resources have suffered degradation due to agricultural activities, including over-exploitation, nutrient contamination, and salinization [4]. Numerous studies have investigated irrigation water requirements. Irrigation, a vital component of agriculture, is defined as the deliberate application of water on agricultural land. In their inventory of currently available options for "enhancing the efficiency of water use in California agriculture," Christian-Smith et al. [5] noted that all of the solutions could be classified as either deficit irrigation, modified irrigation scheduling, or efficient irrigation technologies.

The scarcity of water in various regions underscores the necessity for judicious water management, emphasizing the targeted provision of water to specific areas in required quantities. Farm irrigation system scheduling and planning depend heavily on a careful evaluation of the crops' water needs [6]. Various irrigation techniques, including drip irrigation and sprinkler irrigation, are employed to address the issue of water wastage associated with traditional methods like flood irrigation and furrow irrigation [7]. According to Burt and Styles [8], drip irrigation increases water consumption efficiency by directly delivering precise volumes of water to each plant's root zone. The essential concept of irrigation water requirement is the disparity between the crop's water needs and the effective precipitation [9]. The estimation of both irrigation water demand and crop water requirement can be achieved through the integration of GIS technology with the modified Penman–Monteith equation as recommended by FAO [10]. As per Shen et al. [10] the necessity of irrigation water demand is crucial for allocating water resources to benefit both the economy and natural ecosystems in regions facing significant water deficits. Accurately determining the water needs of crops is essential for enhancing irrigation scheduling. Maintaining environmental quality and effectively managing inputs through practices like irrigation timing and fertilizer use can result in massive returns on agricultural production [11,12]. Therefore, there is a requirement for a method to ascertain the optimal timing for applying water to fields. Nowadays, it has been suggested that crop production use irrigation system automation as a water-saving method [13]. Plant water status or soil moisture are the two main factors that trigger automatic watering systems. In addition to the soil moisture content, other factors that affect plant water status include the surrounding atmospheric demand, plant rooting density, and other plant features [14]. Compared to conventional irrigation systems, automated irrigation systems enable high-frequency irrigation, which keeps the soil water potential (SWP) comparatively constant. To successfully manage irrigation systems, numerous techniques and sensors have been developed [15].

Such a mechanism would alleviate the farmer's workload and assist in maintaining optimal soil conditions for enhanced crop production. A structural system's utilization is reflected in an automated programmed irrigation system, which requires no or very little manual labor beyond inspection [16]. Advances in technology make it feasible to develop systems that minimize the direct involvement of farmers in the irrigation of their fields. Hence, adopting a novel method of gathering real-time data from the field through the utilization of soil moisture sensors presents a genuine opportunity for consistently monitoring the soil water status in agricultural fields. Many sensing devices can be included in sensor systems; scalability is necessary to enable multi-data collecting [17]. Increasing irrigation efficiency in automated irrigation systems has been the subject of several studies. Spectral radiometers have been used to help detect disease [18] and insect infestation [19,20] inside farmed fields, in addition to the use of sensors to remotely monitor crop canopy temperature for the detection of crop water stress. Researchers and farmers are using recently developed electromagnetic sensors extensively for irrigation scheduling. For irrigation scheduling, electromagnetic sensors have been created and are being used, such as t ime-domain reflectometry, electrical capacity ance, and resistance type devices [21, 22, 23, 24, 25].

The affordable nature of the sensor nodes enables the installation of a dense network of soil moisture sensors, effectively capturing the inherent variability in soil moisture within any given field. The primary goal of this paper is to assess the necessity of sensor-based technology for an automated irrigation system, aiming to optimize water usage and save farmers money, electricity, and time.

2. DIFFERENT METHODS USE FOR IRRIGATION

Over time, diverse irrigation techniques have been devised to address the specific water requirements of crops in particular regions. The four primary irrigation methods include surface, subsurface, sprinkler, and drip/micro irrigation, as illustrated in Fig. 1. The choice of an irrigation method depends on factors such as soil characteristics, water availability, climatic conditions, crop types, user expertise and preferences, capital and operational expenses, and the availability of infrastructure. There is no universally ideal irrigation method that can be suitable for all weather conditions, soil types, crop varieties, and achieve 100% efficiency [3].

2.1 Surface Irrigation

In surface irrigation, water is distributed over the soil through gravity. This method can be subdivided into furrow, flooding, and contour farming techniques. According to the International Commission on Irrigation and Drainage, approximately 85% of the world's 299 million hectares of irrigated crop land utilize surface irrigation. Both India and China irrigate over 60 million hectares of cropland each, collectively representing nearly half of the world's irrigated land. In India and China, approximately 95% of the irrigated land relies on surface irrigation [26]. Surface irrigation is frequently regarded as less efficient compared to sprinkler irrigation or micro irrigation, as the water is conveyed through the soil within fields employing surface irrigation.

2.2 Subsurface Irrigation

Subsurface irrigation is a lesser-utilized method in irrigation, involving the elevation or maintenance of the water table near the plant root zone through the use of ditches or subsurface drains for water supply. Sub surface irrigation finds limited application in arid or semi-arid irrigated regions where conventional irrigation is crucial for crop germination. It is commonly employed in tandem with subsurface drainage or controlled drainage systems.

2.3 Micro Irrigation

Sprinkler irrigation involves the application of water to the soil through the sprinkling or spraying of water droplets from stationary or mobile systems. This method is frequently more effective than surface irrigation due to the greater control over water application. In regions characterized by high temperatures and strong winds, sprinkler irrigation may experience notable water losses due to evaporation and wind drift. Ensuring maintenance is crucial for effective sprinkler irrigation, as worn nozzles and leaky pipe connections can diminish application uniformity and overall system efficiency. Drip irrigation involves regular, small-scale water applications through dripping, bubbling, or spraying, typically covering only a specific portion of the soil surface in the field. Adopting drip technology successfully can result in very high yield and water savings [27, 28]. Subsurface drip irrigation has been shown to markedly enhance both crop yield and water use efficiency in comparison to surface irrigation [29].

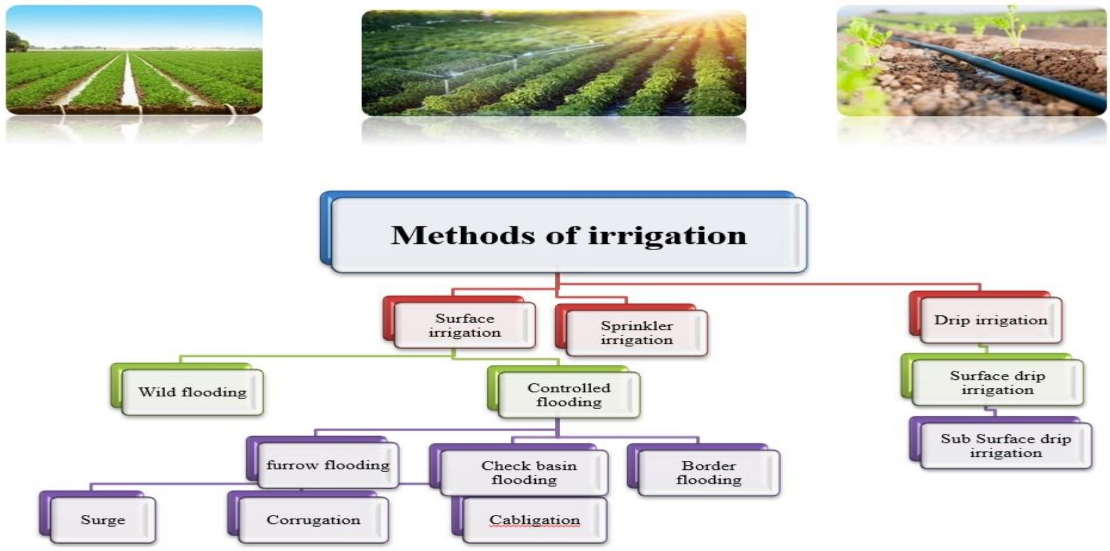

Fig. 1. Different methods of irrigation used in agriculture
Source: https://image.app.google

Table 1. Application efficiencies for irrigation systems

Irrigation Method	Application efficiency
Surface irrigation	
a) Furrow	50-70%
b) Level basin	60-80%
c) Border	60-75%
Sub irrigation	50-80%
Sprinkler irrigation	60-85%
Drip Irrigation	80-90 %

Source: [30]

In the past three decades, endeavors to implement micro-irrigation techniques, including sprinkler and drip irrigation, have been undertaken in various regions globally. Reports indicate that by the year 2024 approximately 8.346 million hectares in India were covered by micro-irrigation systems (drip and sprinkler)

3. APPLICATION OF SENSORS IN IRRIGATION

Soil moisture monitoring serves as a fundamental method for irrigation scheduling, involving the assessment of either the soil water content or the soil water potential [31]. Ensuring optimal irrigation scheduling relies on the crucial practice of monitoring soil moisture at both high spatial and temporal resolutions [32]. Various sensor types, including time-domain transmission, neutron probes, granular matrix, and capacitance sensors, are commonly utilized for assessing soil moisture levels [33].

3.1 Different Techniques use for Sensor Based Irrigation

To assess soil moisture content in both volumetric and gravimetric forms, diverse techniques are available, falling into two categories: (i) classical and (ii) modern methods for both laboratory and in situ measurements. Classical methods for measuring soil moisture include thermo-gravimetric, calcium carbide neutron scattering, gypsum block, and tensiometer techniques. In contrast, modern approaches involve the use of soil resistivity sensors, infrared moisture balance, and dielectric techniques such as Time Domain Reflectometry (TDR), Frequency Domain Reflectometry (FDR), capacitance technique, heat flux soil moisture sensors, micro-electro mechanical systems, and optical techniques [34]. Sensors based on frequency-domain reflectometry (FDR) have the capability to approximate the moisture content of soil in agricultural fields. Placed in proximity to crop roots, the sensors display a moisture content range of 0–50% with a resolution of 0.1%, effectively enhancing water utilization for vegetable crops. Shigeta et al. [35] demonstrated the practical application of real-time soil moisture sensing by establishing correlations between soil volumetric water content (VWC) and the capacitance of inserted sensors, facilitating measurements of soil moisture fluxes. The determination of water content through sensor measurements offers cost-effective real-time, in situ data. In a separate investigation, a total of six capacitance-based sensors, integrated with a data logger, were deployed across three locations [36]. This approach demonstrated enhanced water use efficiency (WUE) when compared to conventional methods. Soil moisture sensors have the potential to enable irrigation tailored to the specific characteristics of a particular crop in a designated field.

3.2 Wireless Sensor Network

These sensors can function independently or be integrated with the FAO method, and they can also serve as a complementary tool for irrigation management based on practical experience. A schematic representation of a distributed in-field Wireless Sensor Network (WSN) is depicted in Fig. 2. The system consists of multiple components referred to as 'nodes.' These nodes are intelligent devices designed for gathering application-specific data requirements. A sensor network carries out three fundamental functions: (i) Sensing, (ii) Communication, and (iii) Computation, employing hardware, software, and algorithms. The nodes play multiple roles in this process. The distributed nodes responsible for collecting information are termed as source nodes, whereas the node consolidating information from all source nodes is referred to as the sink node or the gateway node. The sink node may possess comparatively higher computing capabilities. A source node also functions as a routing node, facilitating multi-hop routing when necessary. The inclusion of an external memory module is optional and might be required for local decision-making data storage needs. In-field sensors observe and assess soil moisture, soil temperature, and air temperature within the field. These sensory data are wirelessly transmitted to a central base station. The base station then analyzes the in-field sensory information using a user-friendly decision-making program and subsequently issues control commands to the irrigation control station [7]. In this system, farmers have the capability to access real-time data, such as soil moisture levels and crop growth status, for their farmland through an Android app or automated SMS notifications, facilitating improved crop management practices. The information obtained from the sensors can guide farmers on optimal irrigation timings and quantities.

3.3 Application of Wireless Sensor Network for Different Crops

Xiao et al. [38] designed a wireless, integrated, frequency-domain soil moisture sensor (WFDSS) specifically for applications in paddy fields in China. This soil sensor had the capability to simultaneously measure soil moisture content and water depth, with the collected data transmitted wirelessly to a centralized data management center. Calamita et al. [39] assessed the suitability of the multi-frequency sensor GEM-300 for the spatio-temporal estimation of soil moisture across hill slopes in four sites within a small mountainous catchment of 32 km^2 in southern Italy. The evaluation involved selecting six frequencies ranging from 7 to 20 kHz for the GEM-300. To determine the conditions under which the GEM-300 sensor

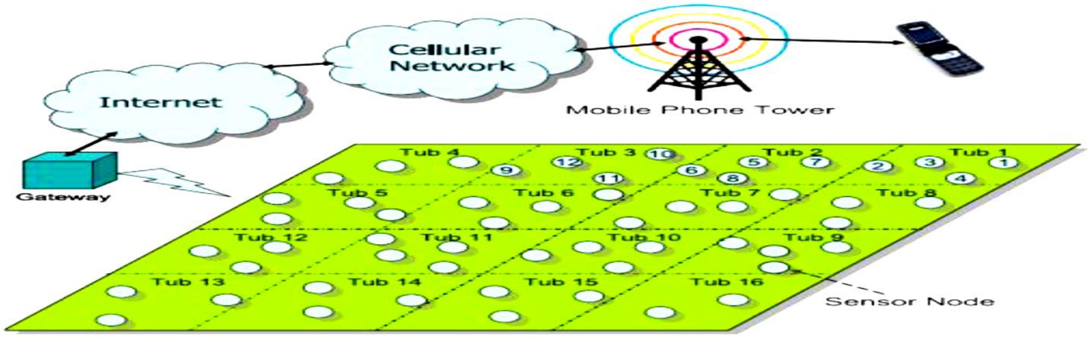

Fig. 2. Wireless sensor network [37]

could effectively capture variations in soil moisture throughout an entire hydrological year, the researchers conducted surveys at multiple sites with diverse soil-landscape characteristics. Utilizing the outcomes of correlation analysis, a linear association was established between electrical conductivity and soil moisture measurements, revealing varying degrees of explained variance (e.g., R2 = 0.46–0.69) and confidence (e.g., RMSE = 3.2–7.8). Optimal outcomes were observed in wooded areas. Furthermore, the study demonstrated a negative correlation between crop production and the electrical conductivity of irrigation water, indicating that crop yields decrease with increasing electrical conductivity. According to Wen-jin et al. [40], rose plants with computer programs controlling automatic watering had somewhat higher heights than those with manual irrigation.

In a separate study by Suvitha et al. in [41], a significant increase in yield (95.11 and 96.21 t/ha) and water use efficiency (21.10 and 25.42 t/ha/mm) was observed in tomato crops during the kharif seasons of 2019 and 2020. This outcome was attributed to the utilization of tensiometer-based drip irrigation, an advanced system capable of real-time monitoring and control. The findings have promising implications for enhancing agricultural practices, conserving water resources, reducing labor, and improving overall farm profitability. Papanikolaou and Sakellariou-Makrantonaki [42] discovered that in fiber sorghum cultivation, the irrigation water-use efficiency (IWUE) was notably higher by 9.5%, reaching 7.50 kg/ha/mm, when employing the automated surface drip irrigation method ASDI100. This method involved supplying water equal to 100% of the crop's evapotranspiration (ETd) using a soil moisture sensor for scheduling, in comparison to the pan surface drip irrigation method PSDI100, which utilized a Class A evaporation pan and a fixed irrigation interval of 2 days.

Panigrahi et al. [43] found that employing soil water sensors for drip irrigation led to a 15% increase in yield, accompanied by the production of higher quality fruits, all while utilizing 20% less water when compared to manual drip irrigation for banana crops. This enhanced yield coupled with reduced water usage resulted in a remarkable 40% improvement in water productivity through sensor-based irrigation. Given these outcomes, utilizing soil water sensor-based irrigation could prove to be a more favourable choice for cultivating bananas in regions with limited water availability. This approach has the potential to expand irrigated areas, ultimately leading to greater production of high-quality banana fruits. According to a study conducted by Chaithra et al. [44], they observed notable variations in water use efficiency (WUE) for maize crops when employing sensor-based irrigation techniques. The research revealed a substantially elevated WUE value (219.2 kg/ha/cm) in the context of sensor-based drip irrigation, specifically when maintaining the soil moisture at 25% depletion, as opposed to employing traditional surface irrigation methods. The increased WUE associated with the drip irrigation approach was attributed to diminished water wastage and improved utilization of water resources by the plants, ultimately resulting in higher crop yields. During the Kharif seasons of 2018 and 2019, Nagarajan et al. [45] conducted an experiment that highlighted the superiority of soil moisture sensor-based drip irrigation. This method outperformed others in terms of both yield (99 t/ha) and water use efficiency (2.52 t/ha/cm), showcasing its effectiveness in enhancing agricultural outcomes.

4. MERIT OF SENSOR-BASED IRRIGATION SYSTEM

The fundamental objective of this system is to administer an optimal quantity of irrigation across the fields. Implementing sensor-based irrigation holds the promise of enhancing both water utilization and economic efficiencies. The prospective economic advantage of this irrigation system is rooted in the reduction of input costs or the augmentation of yield with consistent inputs. Traditional irrigation techniques for farmland necessitate manual involvement, and with the implementation of automated irrigation technology, human intervention can be significantly minimized [3]. The advantages of this technology are evident in the following aspects:

4.1 Water Conservation

Numerous researchers have documented that this system represents the most viable approach for achieving substantial water savings. Reports indicate that integrating sensors with drip and sprinkler irrigation systems can enhance water application efficiency to approximately 80-90%, compared to the 40-45% efficiency typically achieved with surface irrigation methods [46].

4.2 Crop Yield and Economic Returns

According to reports, Zafar et al. [47] noticed that average maximum grain yield of wheat crop was recorded in both sensor-based drip irrigation according to crop water requirement with 100% and 80% recommended dose of fertilizer whereas maximum water productivity observed in sensor-based drip irrigation with 50% management allowed deficiency over other treatments. [35, 48] experimental studies in Egypt to assess the potato yield employing wireless sensor network technology. The results indicated an increase in yields, leading to the recovery of losses amounting to 2 billion pounds annually.

4.3 Sensor and Weather Data Integration

A lot of smart irrigation systems can connect to different sensors, including soil moisture sensors and weather stations. Real-time data gathering and analysis made possible by this connection allow for more precise irrigation decisions. Growers can schedule irrigation more effectively by using soil moisture sensors, which provide information about when to water crops [49]. Kim et al. [50] used distributed wireless sensor networks made up of soil water and temperature sensors to accomplish closed-loop automated irrigation scheduling. Sensor irrigation systems may modify their watering schedules and volumes in response to shifting weather patterns, ensuring that plants receive the proper quantity of water even during erratic weather occurrences.

5. CONCLUSION

Within the semi-arid regions of developing nations, small and marginal farmers, typically those with land holdings ranging from 2 to 4 hectares, rely extensively on rainfall for their crops due to their inability to afford powered irrigation. An observed trend indicates that farmers incur substantial financial losses due to inaccurate weather predictions and inappropriate irrigation methods. In response to the pressing necessity to enhance irrigation system efficiency and mitigate suboptimal water usage, the emphasis is on creating an intelligent irrigation scheduling system. This system aims to empower irrigation farmers to optimize water utilization by irrigating only in locations and times where and when it is necessary, and for the required duration. Upon detecting fluctuations in the temperature and humidity of the environment, these sensors generate an interrupt signal to initiate the irrigation process. These sensor technologies have proven to be effective in gathering real-time data on various parameters related to weather, crops, and soil. This capability contributes to the development of solutions for a wide range of agricultural processes, particularly those associated with irrigation and other agricultural activities. The integration of wireless sensor applications in agriculture opens up avenues for enhancing the efficiency, productivity, and profitability of farming operations.

6. FUTURE SCOPE

The future direction of sensor-based irrigation systems includes integrating seamlessly with the Internet of Things (IoT), employing predictive analytics via machine learning, developing energy-efficient sensors, and creating customized solutions for different crops. Implementing blockchain for secure data management, designing user-friendly mobile applications, and fostering collaborative research for standardization are crucial pathways to improve the effectiveness, sustainability, and accessibility of agricultural practices.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

ACKNOWLEDGEMENTS

Thank you to my mentors, colleagues and reviewers for their invaluable guidance and support throughout the development of this review paper.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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