International Journal on Recent and Innovation Trends in Computing and Communication
ISSN: 2321-8169 Volume: 11 Issue: 6
***Article Received:** 06 April 2023 **Revised:** 01 June 2023 **Accepted:** 30 June 2023*

Review of Sustainable Irrigation Technological Practices in Agriculture

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Abstract- The paper focuses on the increasing demand for water and its impact on irrigated agriculture, emphasizing the importance of effective water management. It reviews the use of soil moisture sensors, IoT, big data analytics, and machine learning in agriculture, particularly in the context of Indian agriculture. The study explores the potential of IoT technologies, such as sensors, drones, and machine learning algorithms, to optimize water usage, minimize waste, and enhance crop yields. The role of big data analytics in sustainable water irrigation management and decision support systems is highlighted. The integration of IoT and sensory systems in smart agriculture is discussed, addressing both the challenges and benefits of implementing sensory-based irrigation systems. Additionally, the paper describes an automated irrigation system developed to optimize water use for crops, utilizing a distributed wireless network of sensors and a web application. The system, powered by photovoltaic panels, demonstrated significant water savings of up to 90% compared to traditional irrigation methods in a sage crop field. The system's energy autonomy and cost-effectiveness suggest its potential utility in water-limited and geographically isolated areas.

Keywords: IOT, Machine Learning, Deep Learning, Smart Irrigation System, Fuzzy Logic, WSN

I. Introduction

Irrigation, as defined by the U.S. Geological Survey, is the deliberate application of water for agricultural purposes, using artificial systems to supply the necessary water when natural rainfall is insufficient. Successful gardening and farming hinge on ensuring crops receive appropriate amounts of water at optimal times. In the delicate balance of irrigation, too little water can lead to withering and death, while excessive water can result in over-saturation, potential mold growth, and crop loss. The water requirements for plants vary based on factors such as the type of crop, prevailing temperatures, soil conditions, and overall weather patterns.

Navigating the complexities of irrigation presents a challenge, and achieving precision can be inconvenient. This is where smart irrigation systems come into play, offering a solution to the uncertainties of traditional watering methods. Smart irrigation systems eliminate guesswork by regulating the amount and timing of water delivery to crops. Users of these innovative systems can program them to activate when the soil is dry and the weather conditions are warm and sunny [26]. Additionally, these systems can be set to pause irrigation if local weather forecasts predict rainfall. Furthermore, users have the flexibility to adjust the hydration levels for each crop based on real-time factors such as precipitation and temperature, providing a dynamic and responsive approach to watering plants on any given day.

The increasing need for water is causing worries about the future of farming in many places. This makes it important to find better ways to use water in agriculture. The old-fashioned ways of watering plants are not very good, sometimes giving too much water in one place and not enough in another [27]. Because of changes in the environment and not having enough water, we really need a better system for watering fields. The study talks a lot about technology, which includes things like sensors, drones, and smart computer programs, and how they can help farmers use water better and grow more crops [29]. The paper finishes by talking about how IoT and smart systems can help achieve important goals for the world, like making sure there's enough clean water for everyone. The goal of this whole review is to help scientists and farmers better understand and use good watering methods for farming that are good for the environment and can be kept up for a long time.

In essence, smart irrigation systems leverage technology to enhance the efficiency and effectiveness of watering practices, taking into account various environmental variables (Figure 1). By automating and optimizing the irrigation process, these systems not only contribute to resource conservation but also relieve farmers and gardeners of the intricate task of manual irrigation management [34]. The integration of smart technology into irrigation not only streamlines the process but also promotes water conservation, making it a valuable tool in sustainable agriculture.

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Figure 1. AI algorithms for Smart Irrigation Systems (SiS)

II. SMART IRRIGATION SYSTEM (SiS)

Smart irrigation systems typically incorporate two fundamental features that play a crucial role in their functionality. The first essential feature is control, which refers to how users manage and regulate the irrigation system. This control can be executed based on weather conditions or soil moisture levels. In essence, the system allows users to set parameters and conditions for when and how the irrigation system should operate [37]. The ability to customize settings based on real-time environmental data provides a level of precision and adaptability that is not achievable with traditional irrigation methods (Figure 2).

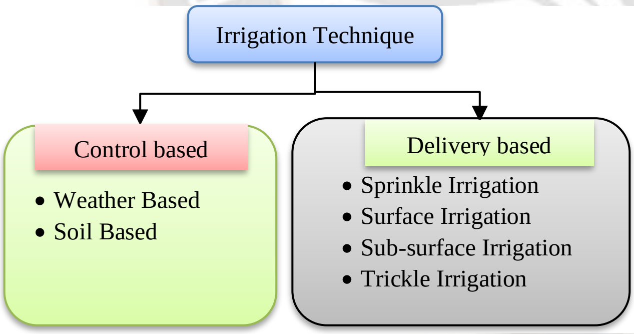

Figure 2. Types of irrigation techniques

The second key feature of smart irrigation systems is delivery, which pertains to the mechanism through which water is supplied to the plants. This includes the type of delivery system employed, such as sprinklers or drip irrigation [38]. The choice of delivery system is significant as it directly influences how water is distributed across the cultivated area. Different crops, soil types, and environmental conditions may require distinct delivery methods to ensure optimal water coverage and absorption. Smart irrigation systems offer flexibility in this aspect, allowing users to select the most suitable delivery system for their specific agricultural needs.

By integrating control and delivery features, smart irrigation systems enable a comprehensive and efficient approach to watering crops (Figure 3). The user-friendly control options empower individuals to tailor irrigation schedules and methods based on the unique requirements of their plants and the prevailing environmental conditions. This adaptability contributes to water conservation, as the system can respond dynamically to changing circumstances, avoiding unnecessary water usage and minimizing the risk of overwatering or underwatering. Overall, the combination of control and delivery features in smart irrigation systems represents a technological advancement that enhances the precision, convenience, and sustainability of agricultural water management.

Figure 2. Delivery based smart irrigation system (SiS)

A. *Control*

Controlling irrigation systems boils down to two fundamental types: weather-based and soil-based. Weather-based smart irrigation systems rely on local weather information to guide watering control, often referred to as an evapotranspiration (ET) system. Evapotranspiration encompasses the loss of water through evaporation from the land surface and the release of water vapor from plants. These systems analyze local temperature, humidity, and wind data to schedule watering activities intelligently. By considering these weather factors, smart irrigation systems can optimize watering schedules based on the environmental conditions, ensuring that plants receive adequate moisture without unnecessary water waste.

On the other hand, soil-based smart irrigation systems focus on measuring the moisture content in the soil to determine the appropriate amount of water to dispense. By assessing soil moisture levels, these systems can be configured to provide water to specific areas, such as root crops, when the soil is dry. Additionally, users have the flexibility to program the system to deactivate once the soil reaches a certain level of saturation. This level of precision allows for the customization of watering schedules for individual crops or designated garden areas, minimizing water wastage and promoting efficient water use.

B. *Delivery*

Smart irrigation systems provide precise control over the hydration of crops, offering users the flexibility to choose from four basic types of water delivery methods: sprinkler, surface, trickle, and subsurface (Figure 4).

- *Sprinkler Delivery:* The sprinkler delivery method mimics natural rainfall by distributing water through the air. Users can configure sprinklers in a fixed position or move them around as needed. This method is versatile and can cover a wide area efficiently.

- *Surface Delivery:* Surface irrigation is one of the oldest methods, dating back over 6,000 years. In surface delivery, water is distributed using gravity through irrigation ditches. This method relies on the natural flow of water to irrigate crops, making it a traditional yet effective approach.

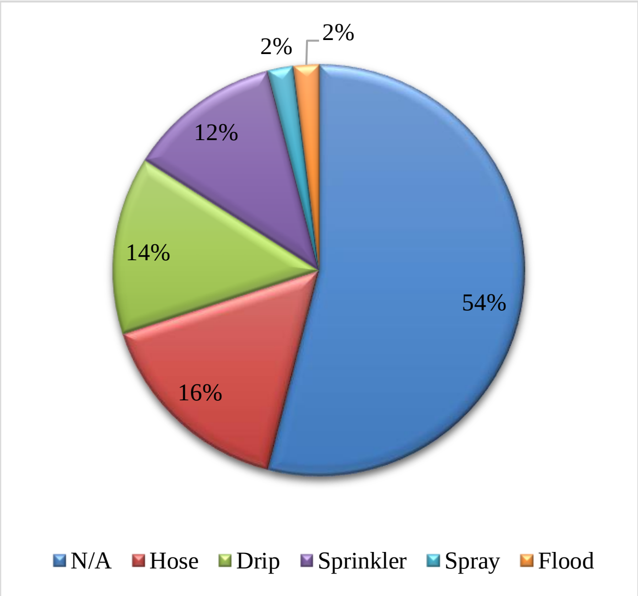

Figure 3. Use of delivery base irrigation techniques

- *Trickle Delivery:* Also known as drip irrigation, the trickle delivery method involves dripping small amounts of water directly onto the soil near the roots of plants. This targeted approach ensures efficient water usage and can reduce water loss due to evaporation. Drip irrigation is known for its precision in delivering water to specific areas.
- *Subsurface Delivery:* The subsurface irrigation method operates below the surface, delivering water directly to the roots of plants. This approach minimizes evaporative water loss and ensures that the water reaches the root zone efficiently. Subsurface delivery is particularly effective in conserving water and promoting the health of plants.

III. COMPONENTS OF SIS

The integration of Internet of Things (IoT) technology has revolutionized smart irrigation systems, enhancing their capabilities through various innovative approaches. integrating IoT with fuzzy logic, ML, big data and neural networks, these systems can achieve intelligent, data-driven decision-making, leading to more efficient water use, reduced waste, and improved crop yields. The ease of data transmission and cloud management further enhances the scalability and accessibility of these smart irrigation solutions. A proposed system combines neural network technologies with IoT for smart irrigation, allowing the system to learn and adapt based on historical data, thereby enhancing its decision-making capabilities in irrigation scheduling [11]. Several references highlight the use of IoT as a foundational element in conjunction with other technologies for smart irrigation applications.

A. *IOT, Big Data and Cloud Computing*

Various innovative approaches to smart irrigation have been proposed, integrating Internet of Things (IoT) technology with advanced methods (Table I). One method introduces automatic irrigation systems that leverage both IoT and fuzzy logic, allowing intelligent decision-making based on real-time data and fuzzy reasoning, ultimately improving water management efficiency in agriculture [1]. Another proposal suggests combining IoT with Machine Learning (ML) algorithms to develop irrigation systems capable of analyzing historical and real-time data for precise adjustments in irrigation schedules, enhancing overall responsiveness [4]. An anti-frost irrigation system has been introduced, integrating IoT and an Adaptive Neuro Fuzzy Inference System (ANFIS) model. Neural networks predict greenhouse temperature, and a fuzzy logic system controls anti-frost measures, showcasing the versatility of IoT in combining different technologies for comprehensive smart irrigation solutions [7]. Capitalizing on IoT's information transmission capabilities and cloud-based data management, another approach enables remote monitoring and control of irrigation systems, providing farmers with real-time information for efficient management [8].

TABLE I. IOT, BIG DATA AND CLOUD COMPUTING BASED SIS METHODS

Technique	Application/Functionality
IoT, Arduino, Raspberry Pi [1]	Data transmission and processing in irrigation systems
IoT, Fuzzy Logic [2]	Smart irrigation systems with fuzzy logic
ML, IoT [4]	ML algorithm for crop irrigation, IoT platform for data visualization
IoT, Cloud [8]	Integration of IoT with irrigation systems
IoT, CNN [11]	Plant state analysis using machine vision
IoT [13]	Disruptive technology in agriculture
IoT, Cloud Computing [46]	Introduces an IoT-based framework for crop production monitoring and automation, aiming to boost crop output and minimize waste.
IoT, SWAMP [47]	Presents the SWAMP architecture for an IoT-based smart water management platform, focusing on precise irrigation in agriculture.

B. *Machine Learning (ML)*

The application of Machine Learning (ML) in smart irrigation systems introduces a data-driven approach to optimize water usage in agriculture. Several innovative approaches to smart irrigation systems have been proposed, highlighting the integration of machine learning (ML) algorithms to optimize water management in agriculture (Figure 5) (Table II). One strategy involves generating alerts based on crop data, providing timely warnings for irrigation initiation to prevent under-watering and ensure adequate moisture [15]. Another approach integrates a neuro-fuzzy system that incorporates ML predictions of soil moisture, utilizing fuzzy logic for an adaptive irrigation management approach [17].

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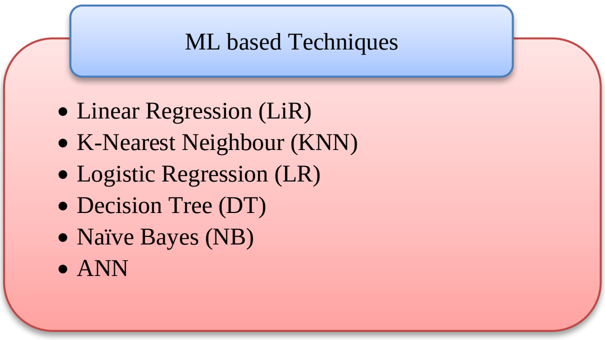

Figure 4. Machine learning based techniques for irrigation

Cost-effective irrigation systems are implemented, leveraging ML algorithms to enhance decision-making processes, integrating various communication protocols, IoT, and ML [18]. Neural network models are employed in systems predicting future soil moisture, considering climate conditions as crucial factors for irrigation scheduling [20]. Data fusion techniques are proposed to enhance sensor network values, utilizing ML models for crop soil moisture and evapotranspiration to improve irrigation decision accuracy [23]. A system based on the impact of plant water stress employs ML technology for image processing, enabling the prediction of suitable irrigation times based on real-time plant conditions [24]. Additionally, irrigation systems incorporating Deep Learning (DL) algorithms, specifically Long Short-Term Memory (LSTM) networks, contribute to more sophisticated and adaptive decision-making processes [25]. These advancements showcase the integration of ML and DL in predictive modeling, emphasizing efficient and effective smart irrigation systems [7]. This data-driven approach enhances the accuracy of irrigation scheduling, optimizing water use in agricultural practices.

TABLE II. MACHINE LEARNING BASED SIS METHODS

Technique	Application/Functionality
Decision Tree [16]	Create an alert for irrigation time based on decision tree algorithm
ANN (Radial Basis Function) [17]	Predict soil moisture in the next hour and compare with required moisture for irrigation control
K-nearest Neighbor (KNN) [19]	Predict irrigation timing based on initial data associated with four soil conditions
ANN [20]	Predict soil moisture with a one-hour timeframe
DL SVM [23]	Data fusion refinement process for classification, regression, and outlier detection
Image Processing Algorithms [24]	Represent water stress impact on plants, decide the best time for irrigation
Random Forest [27]	Search for the best time of day for irrigation
SVM, K-means [28]	Predict soil moisture through a combination of SVR and K-means algorithms
IoT, ML, Precision Farming [40]	Develops a smart management system (SAMS) for precision farming, utilizing IoT and machine learning for enhanced crop production.
SVM, Machine Learning [41]	Evaluates tools and techniques for crop disease prediction, emphasizing the importance of suitable technology for specific regions.
Machine Learning [42]	Develops a crop yield prediction approach using machine learning techniques, emphasizing the role of machine learning in agriculture.
SVM, ANN, Ensemble Model [43]	Investigates a soil database to recommend suitable crops for farmers, employing SVM and ANN in an ensemble model for precision cultivation.
Multiple Linear Regression, Clustering [44]	Analyzes agricultural production forecast using MLR and clustering techniques in a specific area, focusing on improving crop yield predictions.
K-Nearest Neighbor, SVR, ANN, Random Forest [45]	Assesses machine learning methods (K-Nearest Neighbor, SVR, ANN, Random Forest) for accurate crop yield prediction using specific features.
IoT, SEM, Machine Learning [48]	Analyzes the transformation of environmental monitoring into a smart environmental monitoring system (SEM) using IoT and machine learning.

C. Deep Learning (DL)

Deep learning-based smart irrigation techniques in agriculture harness advanced neural network architectures to enhance precision and adaptability in water management. Utilizing algorithms such as convolutional neural networks (CNNs) [18], recurrent neural networks (RNNs) [57], and deep reinforcement learning, these methods (Table III) offer predictive capabilities for crop yield, automate anomaly detection for system maintenance, and enable image recognition for crop health monitoring. By analyzing diverse datasets, including soil moisture, climate conditions, and spatial features, deep learning models facilitate dynamic adjustments to irrigation schedules, optimizing water application. The incorporation of autoencoders enhances the extraction of relevant features from remote sensing data, contributing to accurate environmental impact assessments.

TABLE III. DEEP LEARNING BASED SIS METHODS

Technique	Objectives/Significance
Conventional Neural Network [18]	Choose the proper time for irrigation based on data from different sensors
DL Long Short-Term Memory (LTSM) [25]	Optimize irrigation scheme, suggest the best crop for the next rotation, predict soil moisture one day in advance
GRU Network [50]	Presents a hybrid DL forecasting approach for climate data decomposition and prediction in smart agriculture.
Deep Learning, Data Fusion [51]	Develops a deep learning spatiotemporal strategy for data fusion in agricultural surveillance using remote sensing.
Deep Learning [52]	Introduces a deep learning method for leaf disease detection in various plants, enhancing accuracy and early diagnosis.
Backpropagation Algorithm, LSTM [53]	Compares Backpropagation and LSTM algorithms for plant environmental condition prediction in smart agriculture.
Computer Vision, Deep Learning [54]	Introduces computer vision-based tools and deep learning for plant disease identification and classification in smart agriculture.
Deep Learning, Transfer Learning [55]	Provides an effective object detection architecture in smart agriculture based on deep learning for early disease diagnosis and treatment.
Convolutional Neural Networks (CNNs) [56]	Develops a plant yield forecast model using CNNs based on NDVI and RGB data from UAVs, emphasizing remote sensing and UAVs in smart agriculture.
Feed Forward and Recurrent Neural Network [57]	Develops neural network models (Feed Forward and Recurrent) for crop yield predictions using relevant crop characteristics.
IoT, CNN [58]	Introduces an automated plant disease diagnosis system using IoT, CNN model, and solar sensor nodes for continuous sensing.

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D. Fuzzy Logic (FL)

The application of fuzzy logic in smart irrigation systems brings a level of adaptability and intelligence to the decision-making processes, allowing for nuanced responses to various environmental factors. Several references showcase the diverse ways in which fuzzy logic is integrated into smart irrigation: Smart irrigation systems, [30] introduces an intelligent agent concept employing fuzzy logic to optimize sensor network values, showcasing the adaptability and dynamic decision-making capabilities of fuzzy logic in responding to changing environmental conditions. In a related application, [31] applies a fuzzy logic system with soil moisture and the Crop Water Stress Index (CWSI) as input variables, calculated from plant temperature using an infrared temperature sensor (Table IV). This fuzzy logic system facilitates precise decision-making based on these variables, contributing to effective irrigation management. Furthermore, [32] presents systems with controllers developed based on fuzzy logic and IoT integration to calculate crop irrigation needs. These fuzzy logic controllers consider factors such as soil moisture and environmental conditions to optimize irrigation schedules and water usage. These developments underscore the diverse applications of fuzzy logic and related technologies in optimizing smart irrigation systems.

TABLE IV. FUZZY LOGIC BASED SIS METHODS

Technique	Application/Functionality
Fuzzy Logic, IoT [31-32]	Decision-making for fertilization and crop irrigation in a greenhouse using pH and electrical conductivity variables
Fuzzy Logic [33]	Decision-making based on weather conditions and soil moisture data
Fuzzy Logic, K-means Cluster (Machine Vision) [34]	Fuzzy logic for controlling irrigation water amount, K-means for disease detection
Fuzzy Logic, Solar Energy Panels [35]	Fuzzy logic system with solar energy panels for an electrically autonomous irrigation system
Fuzzy Logic, Firebase (NoSQL), Android [36]	Fuzzy system with soil moisture and available water levels as inputs, data stored in Firebase, viewed in Android app
Fuzzy Logic, Neural Networks [39]	Fuzzy logic for evapotranspiration calculation, neural networks for continuous training
Fuzzy Logic, IoT [59]	Develops an irrigation system based on fuzzy logic and IoT to optimize irrigation frequency and increase production rates.

E. Wireless Sensor Network (WSN)

Wireless Sensor Network (WSN) based smart irrigation techniques in agriculture utilize a network of sensors to continuously monitor soil moisture, weather conditions, and crop health in real-time [14]. These sensors enable data-driven decision-making for precise and efficient irrigation management. By integrating weather monitoring, crop health assessments, and soil moisture sensing, WSN-based systems automate irrigation processes, triggering water application only when specific thresholds are met. The use of localization technologies ensures precision in irrigation, directing water precisely where needed (Table V).

TABLE V. WSN BASED SIS METHODS

Technique	Objectives/Significance
IoT, LoRa LPWAN [3]	Develops an IoT-based water management system with a novel sensor node structure for smart farming.
Wireless Sensors (CSMA, TDMA) [5]	Develops a wireless sensor network for low data rate applications in agriculture, improving watering efficiency.
Electric Double Layer Capacitor (EDLC), WSN [6]	Develops an EDLC-powered wireless sensor network system for monitoring rice field water levels, addressing water intake pollutants.
IoT, Wi-Fi [9]	Creates an IoT gadget for water management, monitoring tank water levels, and controlling water motors for efficient use.
Wi-Fi, IoT [10]	Utilizes Wi-Fi protocol for water quality monitoring, focusing on real-time monitoring and safe water delivery.
IoT, Wireless Sensors [12]	Develops a framework for water level monitoring in lakes using wireless sensor nodes and cloud computing in a cloud setting.
WSN, Optimization Algorithms [14]	Proposes a WSN-based water level monitoring system with optimization algorithms for enhanced information delivery.
Wireless Sensor Network (WSN) [21]	Introduces a WSN-based water monitoring system for large-scale waterways, such as reservoirs, rivers, and lakes.
IoT, Automation [22]	Introduces an automated irrigation system using soil-humidity sensors, IoT, and GSM-GPRS modem for efficient water use.

IV. CONCLUSION

Automated irrigation systems, representing the forefront of precision irrigation, have transformed the labour-intensive process of manual field watering. These systems, equipped with sensors and controllers programmed to monitor soil moisture, weather conditions, and crop water needs, autonomously initiate irrigation when required, eliminating guesswork and promoting water conservation. Benefits include significant water and energy savings, increased crop yields, and reduced labor. Taking this innovation further, smart irrigation systems integrate Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT). Gathering data from diverse sources, these systems make real-time irrigation decisions, adapting to changing conditions and optimizing water usage. The inclusion of user-friendly interfaces enables remote monitoring and control, providing farmers with enhanced efficiency and productivity. This evolution signifies a technological leap towards water-efficient, environmentally conscious, and productivity-focused agricultural practices.

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