

COMPREHENSIVE REVIEW ON SMART IRRIGATION SYSTEM

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Abstract:

Water is one of the most valuable natural resources, and its proper management is crucial for sustainable agriculture. Traditional irrigation methods often lead to water wastage, over-irrigation, or under-irrigation, which can reduce crop yield and harm soil health. To address these challenges, Smart Irrigation Systems have emerged as an efficient and modern solution that uses advanced technologies such as sensors, IoT (Internet of Things), wireless communication, and automation (Gamal *et al.*, 2024; Kaur & Goyal, 2020). This paper focuses on the concept, design, components, and benefits of Smart Irrigation Systems. These systems monitor soil moisture, temperature, humidity, and weather conditions in real-time and supply water to crops only when needed (Mogili & Deepak, 2020; Gutiérrez *et al.*, 2014). By automating the irrigation process, smart systems help farmers save water, reduce energy use, and improve crop productivity (Touil *et al.*, 2022). The integration of mobile apps and cloud-based platforms allows remote monitoring and control, making the system user-friendly and highly efficient. (Peres & Cancelliere, 2021). This review also highlights different types of smart irrigation technologies, real-world case studies, challenges in implementation, and future prospects. The aim is to promote sustainable agricultural practices by reducing water wastage and increasing crop efficiency through smart technology.

1. Introduction

Water is an imperative resource for agricultural activities. Modern irrigation plays a significant role in agriculture by providing the required water for crop cultivation. Smart irrigation is the use of the latest technologies in order to increase productivity and water delivery efficiency. The technologies in use include sensors, internet of things, automated control systems, data analytics, and cloud computing (Gamal *et al.*, 2024; Kaur & Goyal, 2020). Smart irrigation utilizes smart management of the water supply by automating irrigation schedules instead of manual operation, mitigating water wastage and increasing the efficiency of water usage (Kumar & Tripathi, 2023). Water irrigation systems are essential in agricultural activities to improving crop growth. Traditionally, fertilizers and water supply schedules rely on labourer's experience. They normally don't have any scientific calculation or data analysis to discover the best schedule. They normally perform daily irrigation based on experience or needs. Because the fluctuations of soil moisture and other factors, simple irrigation schedule quickly leads to either water overuse or water deficiency (Pardossi *et al.*, 2009; Touil *et al.*, 2022).

The water wastage is growing global concern as the water level in the nature has dropped drastically over the past years. Renewable freshwater area has fallen by a factor of six in the last 100 years. The consumption of water for agricultural activities is the main reason for this crisis. Agriculture uses 75% of fresh water, 20% of irrigation water is not effectively used, and 65% of the crops are affected by the lack of water (Garg & Alam, 2023; Yadav *et al.*, 2024). Smart water irrigation has shown to have assisted in addressing this research problem by increasing water conservation (Peres & Cancelliere, 2021).



Fig - Smart Irrigation Systems

2. Overview Of Irrigation Systems

Various forms of irrigation exist to increase the yield and quality of crops. Irrigation is typically

separated into either surface irrigation or localized irrigation. Surface irrigation involves water distributed over the soil surface via over-the-land flow. Methods of surface irrigation include basin, border-strip, furrow, and wild flooding. The most common surface irrigation method in the world is flooding, which entails water flooding an entire field. It is usually done on smaller fields and requires soil with low infiltration rates. Localized irrigation involves water applied to the soil surface or root zone in a particular area (for example, near the plant or a group of plants). Surface irrigation typically requires more water to avoid non-uniformity due to surface irregularities and wetting patterns. Generally, more control is offered by localized irrigation and the flexibility it provides in water application.

Localized systems provide higher efficiencies compared to surface irrigation when designed, installed, operated, and maintained properly, and they can be managed to provide water to the plant at the right time in the right amount. Drip and micro-irrigation systems are examples of localized irrigation. Garden hose-end sprinkler systems, through which water travels through the air, spray irrigation systems, and rotary sprinkler systems, all fall under the category of sprinkler systems. Sprinkler systems can be permanent or portable and are often used to irrigate lawns and commercial crop fields. Microporous tubing and sprinklers drop irrigation water closer to the ground and also have lower evaporation losses compared to central pivot and drop systems. It is used in small-scale indoor farming and garden setups.

The appropriate irrigation system depends on a number of factors, including the crop cultivated, crop location, soil type, the degree by which the irrigation system can support other agricultural objectives (other objectives include crop temperature control, leaching salts, reducing frost damage, etc.), and available water.

2.1 Traditional Irrigation Methods

Farmers utilize various irrigation systems to sustain crop growth, often selecting methods

based on specific crop needs and geographical factors. Common techniques include surface irrigation, where water flows along the soil surface through open ditches; drip irrigation, which delivers water directly to plant roots via emitters; sprinkler irrigation, distributing water through overhead sprinklers; manual irrigation, involving direct application by hand; and subirrigation, raising the water table to hydrate plants from below. Among these, surface irrigation remains the most widespread, typically requiring prolonged water application periods that can lead to moisture imbalances. Such traditional methods tend to consume large quantities of water, soil, and manpower, falling short of the precise and sustainable practices envisioned in contemporary agricultural frameworks.

Consequently, while effective in maintaining crop hydration, these systems present significant challenges for water conservation efforts and underscore the need for advanced irrigation solutions.

2.2 Modern Irrigation Techniques

Historically, irrigation practices were geared towards survival, with farmers using methods that often-accepted substantial losses without considering efficient resource utilization. Significant water wastage occurred when water sprayer devices sprayed water even in the absence of light from the sun, leading to problems in irrigation. Water scarcity enforces the requirement for efficient use of the water supply. Subsequently, various irrigation techniques started to evolve, including surface or flood irrigation, sprinkler irrigation, localized irrigation, and manual irrigation. All of these techniques are still extensively used across the globe but with both advantages and disadvantages. Large-scale use of water often leads to water scarcity, a serious problem in the future, especially because of the challenging electricity and fuel supply to the farmers. Smart water irrigation techniques have appeared to improve water usage efficiency, delivering water precisely when and where crops need it and minimizing water wastage. Consequently, smart irrigation enhances crop quality and yield, improves profits, minimizes fertilizer leaching, and reduces disease spread and water runoff. It involves the use of monitoring equipment to gather information about crop requirements and

environmental conditions that enable precise irrigation scheduling.

2.3 Smart Irrigation Technologies In the pursuit of efficient water management and increased crop yield, smart irrigation technologies have gained prominence in recent years. These systems rely on the integration of sensors, automated control mechanisms, and data analytics to determine optimal irrigation schedules and adapt to environmental fluctuations. Sensors embedded in the soil monitor moisture levels, temperature, and nutrient balances, providing real-time information for precise water application. Combined with local weather data from meteorological stations or forecasts, these inputs enable the calculation of meaningful parameters such as evapotranspiration (ETO) and crop water stress (CWS), thereby informing automated valves and sprinkler systems on when and how much to irrigate. Beyond water delivery, these components contribute to resource conservation by modulating fertilizer and pesticide use, fostering sustainable agricultural practices. Innovative examples include a smart system that dynamically responds to weather changes, thus reducing operational costs and promoting environmental stewardship. The advent of Internet of Things (IoT) platforms has further bolstered these capabilities by integrating sensing, data processing, and communication tools into cohesive frameworks. By harnessing IoT and wireless technologies, smart irrigation systems achieve seamless automation and remote control, laying the foundation for next-generation solutions that address global water scarcity and food security challenges.

3. Applications

Smart irrigation systems offer numerous economic and environmental benefits, including fair food production, productive farming, and the ability to harvest many agricultural products for various industries. They improve water-use efficiency by leveraging specific irrigation techniques tailored to the crops being cultivated, thus aiding the maintenance of a sustainable ecosystem and lowering production costs.

Smart irrigation systems mitigate hazardous effects on people and agriculture and prevent unemployment caused by economic uncertainties. Farmers find it challenging to monitor crops and water indicators using manual irrigation methods; therefore, smart irrigation systems can effectively control water levels, which in turn supports crop health, helps mitigate droughts, and maintains a safer environment.

Modern irrigation techniques are vital for alleviating water stress in arid and semi-arid regions, enabling the growth of competitive crops by indirectly decreasing soil salinity, enhancing crop production, and ensuring food security. Intelligent irrigation systems achieve this by automating irrigation based on crop types identified through images captured by smartphones or cameras equipped with deep learning models and subsequently recommending the appropriate amount of water.

3.1 Water Conservation

Water conservation stands out as the primary motivation for the development of smart irrigation systems. Agriculture's high-water demands can severely restrict supplies for other domestic uses, for industry, and for ecosystems. Agriculture is also deeply vulnerable to the vagaries of the weather; irrigation systems thus provide essential assurance against food shortages due to drought. Efficient irrigation scheduling is widely recognized as a principal measure to improve water use efficiency in agriculture. Modern smart systems enable precise control of irrigation in both time and space. Their components can include sensors, controllers, communication networks, and analytical tools. Typically employing soil moisture observations, such technologies reveal when and where irrigation is needed, along with the appropriate amount. Curtailing irrigation in cases where soil moisture is already adequate clearly stands as the principal way to limit water consumption. But an ability to conserve groundwater and maintain appropriate water tables, without significantly over- or under-watering, also serves crucial purposes. Associated with such aims is a broader objective to capture current crop-soil-climate interactions and assess the crop's actual development stage,

the state of its canopy cover, and the extent of its root system. Irrigating the soil at the root zone inhibits evapotranspiration, promotes efficient fertilization, and facilitates biological nitrogen fixation. These observations also, in turn, offer quantitative insights into how irrigation demands evolve over time, in response to both cropping strategy and plant growth.

3.2 Cost Efficiency

Smart irrigation enables operational savings through automated systems that avoid excessive water application and associated labor costs. The initial investments and ongoing maintenance expenses for purchasing and deploying the technology remain approximately 30 percent greater than conventional systems. Corresponding benefits encompass reductions in utility and labor costs, as well as additional gains that offset these expenses. Determining the economic advantage for a specific system entail evaluating environmental and design variations that directly influence values and conducting technical assessments to calculate precise benefits.

Numerous configurations are feasible when developing a customized smart irrigation apparatus because the term broadly encompasses various technologies, ranging from simple moisture sensors to complex systems incorporating multiple inputs and remote-control capabilities. The scope of available options has expanded and diversified in recent years due to technological advancements that have broadened applications across diverse environments. Efforts have also concentrated on creating more sophisticated and cost-effective methodologies.

3.3 Improved Crop Yield

Smart irrigation has become an effective tool for water conservation, especially in water-limited regions, with potential to increase crop yield and quality. It employs one or multiple sensors measuring soil moisture, temperature, rainfall or other parameters and combines feed-forward and feedback control using the data to determine when and how much to irrigate. This guarantees sufficient irrigation to sustain crop growth while simultaneously avoiding unnecessary water depletion, enabling a given quantity of water to

irrigate a larger cultivated area than under traditional irrigation scheduling.

Crop yields increase both because the precision in water supply promotes plant health and because it improves the carbon and nutrient balance in the soil. For instance, the application of wastewater decreases crop yields due to high salinity and the presence of heavy metals. To overcome this problem, a smart irrigation system is used to dilute the wastewater with freshwater to a predetermined concentration threshold before irrigating maize crops. This method has been shown to apply water more efficiently and to generate 35% higher crop yields. Similarly, fresh water requirements can be significantly reduced while simultaneously increasing yield by applying smart irrigation based on moving slope and threshold evaluation parameters augmented with machine learning-based weather prediction approaches.

4 Challenges in Implementation

Previous evidence demonstrated that smart irrigation can reduce water consumption and enhance crop productivity, yet multiple barriers impede rapid commercial adoption. First, the initial investment required to purchase and install smart irrigation systems remains substantially higher than that for traditional irrigation, posing a significant barrier especially in regions with a

high import tax or weak currency. Second, the lack of comprehensive mass media coverage and educational programs often leaves farmers unconvinced about the effectiveness of smart irrigation solutions; surveys suggest that experience and training dramatically increase willingness to adopt these technologies. Finally, many smart irrigation systems necessitate the user to still perform maintenance and repairs of sensors, valves, and control units, discouraging those with limited technical expertise. Addressing these challenges remains critical to accelerating the widespread implementation of smart irrigation technologies.

4.1 High Initial Costs

The high initial cost of smart irrigation equipment remains a significant barrier to widespread adoption. The main expenses

quantify in sensor networks and infrastructure, not in consumables. The expense lies in precision technologies capable of frequent, accurate soil moisture measurement and automated irrigation control. Extensive sensor deployment and networking are prerequisites for effective management.

Currently, most farmers base irrigation decisions on experience rather than objective data. Market limitations can push towards excessive use instead of the scientifically optimal quantity. In many areas, irrigation follows routine timing and localized rules of thumb, neglecting critical parameters.

4.2 Technical Expertise Requirement

Smart irrigation represents an approach to water management that utilizes modern sensor, control, and wireless technologies in order to sustain optimal soil moisture content at the root zone and improve water use efficiency for crop cultivation. Like many other domains, smart irrigation paves the way for a novel paradigm in agricultural productivity and water conservation, where intelligent systems leverage innovations in sensing, cloud computing, and telecommunications to automate irrigation and allow more efficient use of water across a wide variety of growing environments and conditions.

Interest in smart irrigation has surged in recent years on account of fresh developments in sensor and artificial intelligence technology, which allow for far greater application of intelligent processing at the level of autonomous devices and systems. The sensor systems themselves have become considerably more accurate in their estimation of soil moisture, temperature, humidity, and similar parameters, while wireless technologies enable real-time data transmission to remote monitoring stations and cloud-based services for further analysis. At the same time, novel approaches to processing high-density signals such as artificial neural networks and machine learning for foreground-extraction and track reconstruction enable greater use of objective measurement and allocation, thus permitting natural environmental influences to be estimated with higher accuracy and the implementation of irrigation systems accordingly.

Smart irrigation systems come in a variety of forms, of which drip, sprinkler, and sub-surface irrigation constitute the major types of interest. Drip irrigation represents a simple, efficient method that works by delivering water directly to the root zone through a huge network of valves and piping. Sprinkler irrigation traces its origin back to the mid-twentieth century, and spreads water over the broad surface of a landscape with low sensitivity to pattern-layout. Subsurface irrigation applies water directly below the surface where coverage and scale are critical and often requires more delicate, tailored solutions. In each case, wavelength and power-level control, device calibration, and sensing accuracy enable precise, detailed allocation of water with minimal waste. State-of-the-art models are equipped with distributed management and are well-suited for a wide variety of growing environments and conditions.

Relative to traditional irrigation techniques, smart irrigation offers numerous benefits for efficiency, effectiveness, and general performance. Greater precision allows a significant reduction in water consumption, such that smart irrigation has the potential to reduce consumptive use on commercial farms by 20-50%, with associated cost savings in energy and other capital expenditures. Given the global challenges of water supply and pressure on aquifer resources in many regions, the technology holds considerable promise. In arid regions, for example, improvements in efficiency enable the productive use of water otherwise too marginal for agricultural exploitation at scale. The reduction in excessive supply also helps suppress the mechanisms by which waterborne nutrients transition into a broad range of water bodies. Finally, by monitoring soil moisture content over time, smart irrigation provides growers with ongoing information about changing patterns in water availability, clays, salinity, and groundwater flow, which can be an important consideration for a wide variety of crops.

4.3 Maintenance and Reliability Issues

Maintenance is critical for smart irrigation systems, as timely and proper upkeep ensures their operational reliability and longevity. These

systems operate in harsh conditions, exposing electronic components to weather elements. Risks include failures due to component wear and damage caused by animals. Critical vulnerabilities involve power supplies, sensors, and communication modules, which must be regularly checked and maintained to ensure continuous operation. Despite their advantages, smart irrigation systems face challenges related to installation and maintenance, particularly in larger and more complex deployments.

5. Effective smart irrigation system using IOT and Ai module

1. IoT in Agriculture

IoT, a term coined by Ashton in 1999, describes an interconnected vision encompassing things, computing, communication, and semantics. IoT combines the Internet, sensors, embedded systems, and intelligent technologies to create a vast network of interconnected smart objects. The widespread adoption of smart technologies provides unique opportunities for controlling and monitoring IoT devices. IoT has already been successfully implemented in various areas, including agriculture. Considering the core elements of smart agriculture, IoT technology plays a crucial role in improving monitoring and control capabilities during the production process. Nonetheless, IoT applications generate massive amounts of data, which require human intervention for interpretation and decision making. Thus, various approaches have been developed to extract, analyze, and understand these data streams. Current research focuses on integrating IoT with artificial intelligence (AI) and machine learning techniques to build intelligent monitoring and decision-

2. Artificial Intelligence in Smart Irrigation

Integrating AI into smart irrigation provides an intelligent approach to farming through assessment and autonomous decision-making capabilities. This technology enables agriculture systems to self-optimize operations and accommodate additional external variables and inputs. IoT-equipped smart irrigation, powered by artificial intelligence, delivers rapid, accurate, and efficient outcomes [1]. An intelligent irrigation system leverages data-processing techniques to prepare and maintain essential

information for a specific farm, assisting farmers in scheduling irrigation based on critical assessments. Such devices identify each factor influencing the system's operation and collect related data [3]. While the hardware components are integral to the architecture, the AI module facilitates the processing of agricultural data and the formulation of appropriate irrigation decisions (see Section 5). Through a combination of sensors, actuators, communication modules, and control units, the system captures, interprets, and implements decisions designed to optimize water use and enhance productivity.

6. Case Studies

Smart irrigation systems combine autonomous irrigation with feedback control based on climate, crop, soil, and groundwater information to achieve efficient water management and crop growth. Active research has led to numerous studies and commercial products worldwide. The technology maintains an optimal water balance by integrating automatic systems with feedback control, enabling precise management of water supply and demand in cultivated areas.

Case studies illustrate the successful application of smart irrigation on greenhouses, arithmetic parks, streetscapes, golf courses, and sports fields. These systems provide reliable data without compromising the quality of the irrigated regions, thereby enhancing water management efficiency. In specialized agricultural and landscape settings, smart irrigation ensures satisfactory outcomes throughout the year.

1. Agricultural Use Cases

Implementing automated irrigation systems is a recognized approach to reduce overall water consumption, a critical issue in water-scarce regions. Key environmental parameters affecting irrigation include soil characteristics, such as soil moisture and temperature, precipitation, water quantity and quality, solar radiation, and additional weather data. Sensor-based monitoring of these factors enables automation of irrigation operations, optimizing water usage for field applications. Internet of Things (IoT) technology supports the integration of intelligent control systems, controllers, and probes, facilitating

efficient management of irrigation activities.

Smart irrigation provides farmers with a decisionmaking mechanism that allows them to irrigate land only when necessary and with the appropriate amount of water. While various methods exist, many rely on electrical sensors installed underground, which can face limitations in granular precision and installation complexity. As agriculture demands the application of cutting-edge technologies, IoT emerges as a candidate for managing several services with reduced human intervention. Nonetheless, the installation of automated agricultural systems presents technical and economic obstacles, requiring a trade-off between environmental concerns and economic resources.

Rice farming, a significant water consumer worldwide, exemplifies the impact of uncontrolled water use on the environment. Advancing climate change prompts the search for more efficient and sustainable rice farming methods. An IoT-based smart water irrigation system offers an accurate and innovative solution to uncontrolled water consumption, integrating sensors such as soil moisture, pH, water level, temperature, rain detection, and GPS modules for optimal operation. Measurements are securely transmitted via an IP gateway to cloud infrastructure for data analysis and decisionmaking. A user-friendly application enables remote monitoring and autonomous regulation of soil irrigation through a web interface, facilitating real-time interaction with sensors and minimizing power consumption, thereby extending system longevity. The BLYNK application supports this approach, offering a streamlined IoT development process and customizable interface compatible with various hardware platforms and communication protocols. This system aims to enhance farmers' productivity and quality of life while reducing human involvement. Renewable energy sources, such as photovoltaic panels, are recommended to address power needs by charging batteries during periods of surplus energy.

Daily watering operations, particularly in rice cultivation, depend on environmental data for real-time assessment. Humidity, temperature, and soil moisture measurements inform

timely

notifications to farming staff's mobile devices, indicating precise irrigation requirements. This approach conserves water used for irrigation while maintaining crop health.

2. Urban Landscape Management

Urban landscape management consumes significant water resources, primarily through landscape irrigation. Urbanization has increased pressure on water resources for landscape irrigation, heightening environmental and economic concerns. Smart irrigation systems can substantially reduce water consumption on green surfaces in public parks, gardens, and sporting venues.

7. Comparative Analysis of Smart Irrigation Systems

The increasing demand for smart irrigation systems in the agricultural sector requires a thorough study of existing alternatives. This study focuses on topic analysis, providing a comparative review of common smart irrigation strategies and classifying them according to geographical location, system benefits, and challenges.

Smart irrigation precision and water savings connect to various smart irrigation strategies for different regions and environments. As a critical tool for sustainable agricultural water management worldwide, governmental and societal support drives the integration of smart irrigation with advanced technologies. These technologies facilitate scalable and accessible control and monitoring in both urban and rural settings.

At country levels in Asia, Europe, and America, drip and sprinkler based smart irrigation systems dominate agriculture; drip-based systems also garner interest in urban and sports applications. The environmental compatibility of subsurface smart irrigation systems positions them as an appealing choice for Asian and American agricultural contexts. Consequently, desires to reduce water consumption, minimize nutrient leaching, increase crop quality and quantity, and lower societal costs underline the widespread

demand.

Despite promising benefits like water savings, pest and weed control, and efficient automation, smart irrigation systems face barriers to adoption. High installation expenses, reliance on extensive sensor networks, required development settings, and accessible calibration and maintenance services limit uptake across diverse regions. Continued technological advancement and successful reconciliations of benefits and challenges will increase smart irrigation prevalence and acceptance worldwide.

8. Conclusion

Recent developments in sensor technology, automation, and data analysis have prompted increased interest in water scarcity challenges and the horticulture sector. Irrigation scheduling is a dynamic decision-making process that relies on many associated factors including climate forecasting, technological trends, and market prices. Smart technologies have been applied to the irrigation operation involving many components, including water delivery, monitoring, sensing, and control mechanisms, to create an automated and easy-to-manage system.

Smart irrigation allows users to monitor and control water distribution to their plants remotely using a device such as a smartphone. This technology can improve irrigation efficiency and prevent the overuse of water by delivering water to plants only when necessary. Smart irrigation systems use weather data and soil moisture levels to determine the appropriate amount of water for each plant. Smart irrigation systems help gardeners and agriculturists deliver water efficiently, saving time and preventing plants from drying out or suffering from overwatering. This review addresses the principles, types, benefits, challenges, and applications of smart irrigation systems. The future trends and recommendations for further development of these systems are also discussed.

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