

Water-Smart Agriculture: Efficient Irrigation and Water Conservation Technologies

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Received: 2.08.2025 | Revised: 16.09.2025 | Accepted: 9.10.2025

ABSTRACT

Water scarcity represents one of the most pressing challenges confronting global agriculture in the twenty-first century. Agriculture accounts for approximately 72% of global freshwater withdrawals, yet conventional irrigation methods suffer from efficiencies as low as 40–55%. This review paper comprehensively examines water-smart agricultural technologies, encompassing efficient irrigation systems and water conservation strategies that address the dual imperatives of food security and sustainable water resource management. The paper evaluates traditional and modern irrigation methods, including drip irrigation, sprinkler systems, subsurface drip irrigation (SDI), and Internet of Things (IoT)-based smart irrigation systems. Additionally, water conservation practices such as deficit irrigation, mulching, and rainwater harvesting are critically reviewed. Findings indicate that IoT-based smart irrigation can reduce water consumption by 35–50% while simultaneously increasing crop yields by up to 43%. The integration of artificial intelligence, sensor technologies, and cloud computing in precision irrigation offers transformative potential for achieving the goal of “more crop per drop.”

Keywords: *Water-smart agriculture, Drip irrigation, IoT-based irrigation, Water use efficiency, Precision agriculture.*

INTRODUCTION

Water is the lifeblood of agriculture, yet it is rapidly becoming one of the most constrained resources globally. According to the Food and Agriculture Organization (FAO, 2025),

renewable freshwater availability per person has declined by 7% over the past decade, with agriculture remaining the largest water-using sector, accounting for 72% of withdrawals in many regions.

Cite this article: Bindu, S., Paikra, P. S., Sharma, S. K., & Meena, N. K. (2025). Water-Smart Agriculture: Efficient Irrigation and Water Conservation Technologies, *Curr. Rese. Agri. Far.* 6(5), 22-30. doi: <http://dx.doi.org/10.18782/2582-7146.296>

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Approximately 3.2 billion people currently live in water-stressed agricultural areas (FAO, 2020), and without sustainable water management, countries such as Iraq risk losing up to 50% of their wheat and barley yields by 2050 (FAO, 2025). Globally, agricultural production is responsible for over 70% of freshwater water withdrawal volume (Aivazidou et al., 2016), while irrigated agriculture, covering only about 20% of cultivated land, contributes 40% of total food production worldwide (World Bank, 2022).

The challenge is compounded by population growth, urbanization, and climate change, which collectively increase the competition for finite water resources across agricultural, industrial, and domestic sectors. Traditional irrigation methods, including flood and furrow irrigation, remain widely practiced in many developing regions despite their inherently low water use efficiency of 40–55% (Lamm et al., 2021). These conventional approaches lead to excessive water losses through evaporation, deep percolation, and

surface runoff, exacerbating water scarcity and contributing to soil degradation, waterlogging, and salinization (Ayars et al., 2015).

In this context, the concept of “water-smart agriculture” has emerged as a paradigm that integrates efficient irrigation technologies with water conservation strategies to achieve the objective of “more crop per drop” (World Bank, 2022). Water-smart agriculture encompasses a spectrum of interventions ranging from precision drip and sprinkler systems to cutting-edge Internet of Things (IoT)-based smart irrigation systems that leverage real-time sensor data, cloud computing, and artificial intelligence (AI) for optimizing water application (Al-Ghobari & Dewidar, 2018; & Kumar et al., 2024). This review aims to critically examine the current state of efficient irrigation technologies and water conservation practices, synthesize evidence on their effectiveness, and discuss future directions for sustainable agricultural water management.

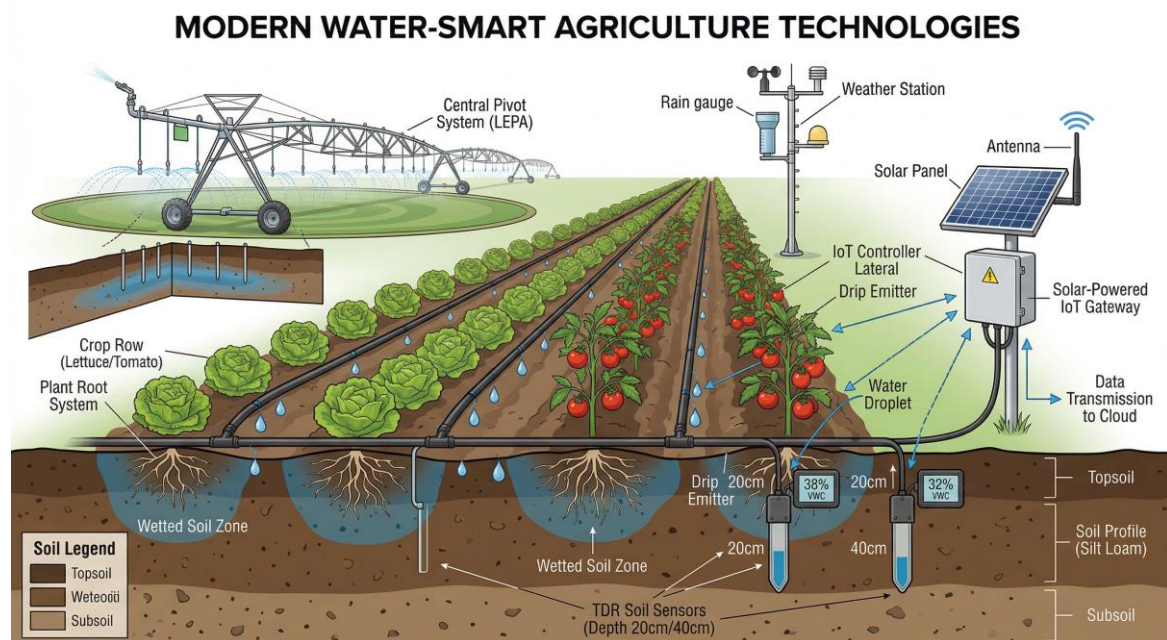


Figure 1: Conceptual overview of modern water-smart agriculture technologies integrating drip irrigation, soil moisture sensors, weather stations, and IoT gateways.

2. Global Water Crisis in Agriculture

The global water crisis in agriculture is a multifaceted challenge driven by increasing demand, declining supply, and the impacts of

climate variability. The FAO AQUASTAT 2025 Water Data Snapshot reveals that freshwater withdrawals have increased in several regions, with Northern Africa

witnessing a 16% rise over the past decade, while countries such as Kuwait and Qatar rank among the lowest in renewable water resources per person globally (FAO, 2025). Water stress levels remain high or very high in countries where withdrawals regularly exceed renewable supplies.

More than 80% of global agricultural land is rainfed, consuming only green water (rainfall), while approximately 20% of total cultivated land is irrigated with blue water, contributing 40% of total food production (World Bank, 2022). Irrigated agriculture is,

on average, at least twice as productive per unit of land as rainfed agriculture, underscoring the critical importance of irrigation (World Bank, 2022). However, it has been estimated that nearly 40% of the global food supply is produced by irrigation agriculture, making irrigation water the largest single consumer of water on earth (Ayars et al., 2015). The shortage of irrigation water due to competition from industry and urban consumption threatens food security worldwide.

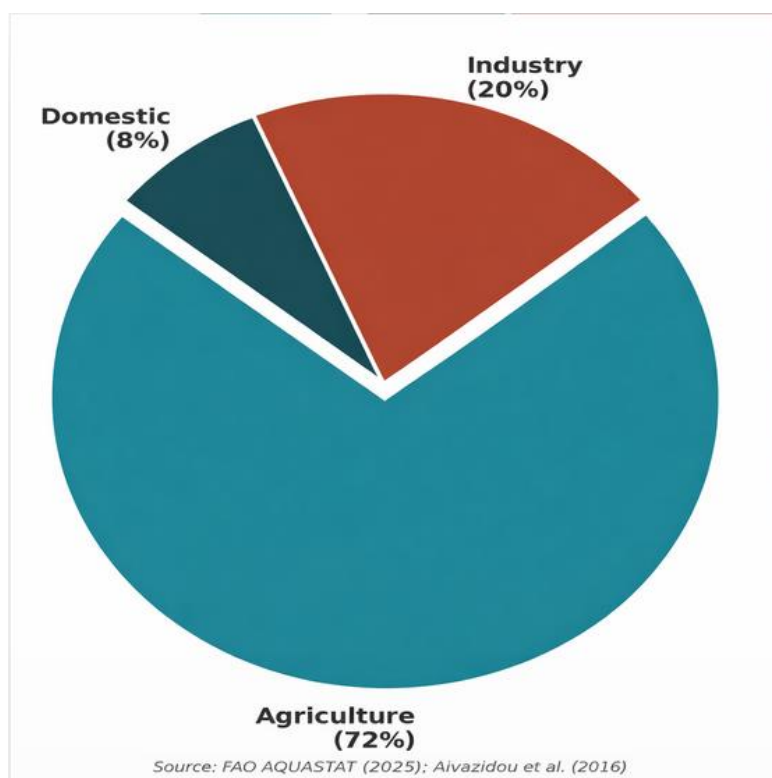


Figure 2: Distribution of global freshwater withdrawal by sector, showing agriculture as the dominant consumer at 72% (FAO AQUASTAT, 2025).

Climate change further intensifies these challenges through altered precipitation patterns, increased frequency and severity of droughts, and rising temperatures that elevate crop water requirements. Drought ranks among the top environmental phenomena associated with billion-dollar weather disasters (Mancosu et al., 2015). Future demand for water across all sectors will require 25–40% of water to be reallocated from lower to higher productivity activities, particularly in water-stressed regions, with this reallocation

expected primarily from and at the expense of agriculture (World Bank, 2022).

3. Efficient Irrigation Technologies

3.1 Drip Irrigation Systems

Drip irrigation represents a significant advancement over conventional flood irrigation, delivering water directly to the plant root zone through a network of emitters, pipes, and tubing. This method achieves application efficiencies of approximately 90%, compared to 40–55% for flood and furrow systems (Camp, 1998). Surface drip irrigation reduces

water losses from evaporation, runoff, and deep percolation by maintaining soil moisture within the optimal range for plant uptake (Lamm et al., 2021). Research demonstrates that micro-irrigation promotes soil water extraction in deep soil layers by improving root length density below 80 cm, increasing yields by 9.8–14.2% and improving water use efficiency (WUE) by 12.3–17.7% compared to traditional flood irrigation (Li et al., 2018).

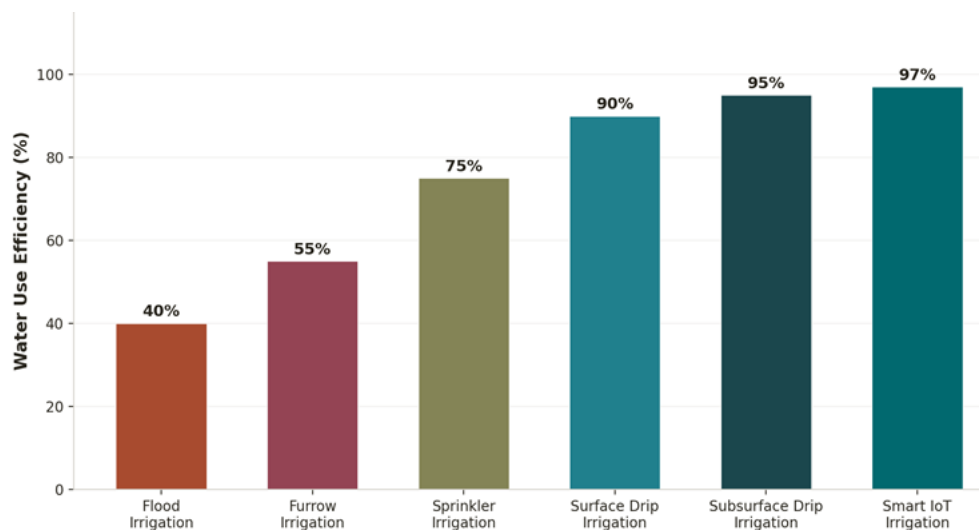
3.2 Subsurface Drip Irrigation (SDI)

Subsurface drip irrigation (SDI) involves the placement of drip laterals below the soil surface, directly within the root zone, achieving application efficiencies exceeding 90–95% (Camp, 1998). SDI could save up to 25–50% of water compared to surface irrigation methods (Lamm et al., 2021). Camp (1998) found that yields for SDI-irrigated crops were equal to or greater than yields from other methods of irrigation, while some investigators reported irrigation water requirements as much as 40% less than for other irrigation methods. Deficit subsurface

drip irrigation at 0.6 ETc significantly increased soil water extraction from 40–80 and 80–140 cm depths from jointing to maturity, demonstrating that regulated deficit irrigation under SDI can optimize water use without compromising yields (Yang et al., 2020).

3.3 Sprinkler Irrigation Systems

Sprinkler irrigation, including centre pivot and lateral move systems, provides uniform water distribution across large fields with application efficiencies of approximately 75–85% (Lamm et al., 2021). Modern low-energy precision application (LEPA) sprinkler systems further improve efficiency by applying water at or near the soil surface, reducing evaporation losses. These systems are particularly suitable for large-scale agricultural operations where uniform coverage is essential. While less water-efficient than drip systems, sprinklers offer advantages in terms of ease of management, fertigation capability, and adaptability to various terrain conditions (Waller et al., 2020).



Source: Compiled from FAO (2020); Camp (1998); Lamm et al. (2021)

Figure 3: Comparison of water use efficiency (%) across traditional and modern irrigation methods, from flood irrigation (40%) to IoT-based smart systems (97%).

3.4 IoT-Based Smart Irrigation Systems

The Internet of Things (IoT) has revolutionised irrigation management through the integration of real-time sensor networks, microcontrollers, cloud computing, and artificial intelligence. Smart irrigation systems use soil moisture sensors, temperature and

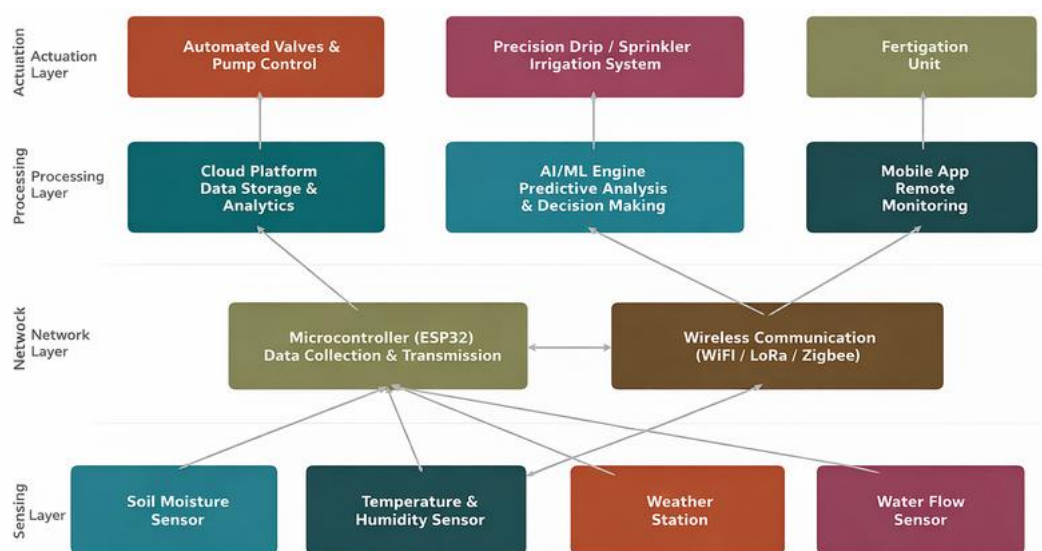
humidity sensors, weather stations, and water flow sensors to continuously monitor field conditions and automate irrigation decisions (Kumar et al., 2024). According to the Environmental Protection Agency (EPA, 2016), smart irrigation controllers can reduce outdoor water use by 20–50%, while Dandy et

al. (2018) found that they improve irrigation efficiency by as much as 30%.

A recent study by Alwan et al. (2026) demonstrated that an IoT-based irrigation system using the ESP32 microcontroller, integrated with soil moisture, temperature, humidity, and light intensity sensors, reduced water consumption by 47% while achieving a 43% increase in crop yield. The system maintained optimal soil moisture thresholds and enabled continuous monitoring and real-time decision-making. Similarly, research integrating Decision Tree Classifier and Random Forest Classifier algorithms with IoT sensors achieved an irrigation scheduling accuracy of 98.7% (Kumar et al., 2024), significantly outperforming conventional

methods while maintaining computational efficiency.

AI-powered smart irrigation systems leverage machine learning algorithms to analyze historical data, weather forecasts, and plant requirements for predictive irrigation scheduling. Cloud-based monitoring platforms enable farmers to remotely monitor and control irrigation settings via mobile applications, a feature particularly beneficial for large-scale operations (Al-Ghobari & Dewidar, 2018). These systems represent the convergence of precision agriculture, data science, and automation, offering a viable pathway toward sustainable and climate-resilient farming.



Source: Adapted from Al-Ghobari & Dewidar (2018); Kumar et al. (2024)

Figure 4: Layered architecture of an IoT-based smart irrigation system comprising sensing, network, processing, and actuation layers.

4. Water Conservation Strategies

4.1 Deficit Irrigation

Deficit irrigation (DI) is a water management strategy that deliberately applies water below the full crop water requirement during specific growth stages, aiming to maximize water use efficiency without significant yield penalty. Research has shown that applying moderate water stress can stimulate the redistribution of photosynthetic products from vegetative parts (leaves and stems) to reproductive tissues (roots and fruits), thereby enhancing water

conservation while maintaining acceptable crop yields (Yang et al., 2020). Regulated deficit irrigation at 75% of field capacity has been found to increase vegetative growth, plant height, biomass, and total productivity compared to full irrigation in certain crop systems (Alwan et al., 2026). Deficit irrigation and mulching together significantly increase water use efficiency for various crops (Kassa et al., 2023).

4.2 Mulching

Mulching is a widely adopted conservation practice that involves covering the soil surface with organic or synthetic materials to reduce evaporation, maintain soil moisture, suppress weeds, and regulate soil temperature. Organic mulches such as straw, wood chips, and compost enhance soil structure, boost water-holding capacity, and increase nutrient content (Verdesian, 2024). Drip irrigation combined with mulching represents one of the most effective water conservation combinations, reducing water usage by 15–30% compared to bare soil conditions. Black plastic mulch, particularly woven varieties that allow water infiltration, prevents evaporation while permitting rainfall to reach the root zone (Lincoln Conservation, 2024).

4.3 Rainwater Harvesting

Rainwater harvesting involves the collection, storage, and utilization of precipitation that would otherwise be lost to runoff. In agricultural settings, rainwater harvesting can be implemented through farm ponds, check dams, contour bunding, and rooftop collection systems. This strategy is particularly valuable in rainfed agricultural areas where more than 80% of global agricultural land depends solely on rainfall (World Bank, 2022). The captured water can be used to supplement irrigation

during dry periods, reducing dependence on groundwater extraction and surface water diversion. Integrated approaches combining rainwater harvesting with efficient irrigation systems can achieve water savings of 20–35% (Cropin, 2021).

4.4 Irrigation Scheduling and Soil Moisture Monitoring

Proper irrigation scheduling is a fundamental water conservation technique that involves determining the optimal timing, frequency, and volume of irrigation based on crop type, growth stage, soil moisture levels, and weather conditions. Advanced agricultural technologies, including soil moisture sensors and weather-based evapotranspiration (ET) controllers, enable precise monitoring and informed decision-making about when to irrigate (EPA, 2016). Soil tensiometers and time-domain reflectometry (TDR) sensors provide real-time soil moisture readings that integrate with automated irrigation systems to prevent both over-watering and under-watering (Verdesian, 2024). Studies have demonstrated that adequate irrigation scheduling reduces the water needed by decreasing evaporation and providing water precisely when plants require it (Lincoln Conservation, 2024).

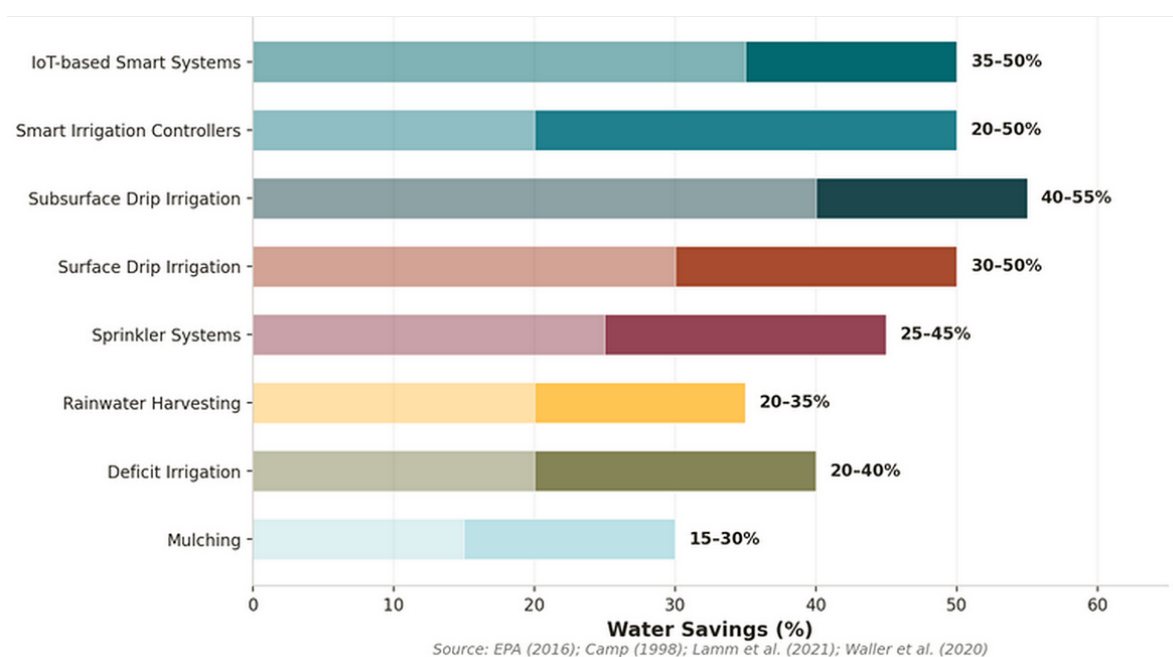


Figure 5: Water savings potential (%) of various agricultural water conservation technologies, ranging from mulching (15–30%) to IoT-based smart systems (35–50%).

5. Comparative Analysis of Irrigation Technologies

A comprehensive comparison of irrigation technologies reveals substantial differences in water use efficiency, cost implications, and

applicability across different farming scales and contexts. Table 1 summarizes the key characteristics of various irrigation systems discussed in this review.

Table 1: Comparative Analysis of Irrigation Technologies

Irrigation Method	WUE (%)	Water Savings	Cost	Scalability	Key Advantage
Flood Irrigation	40–55	Baseline	Low	Large fields	Low initial cost
Sprinkler	75–85	25–45%	Medium	Large fields	Uniform coverage
Surface Drip	85–90	30–50%	Medium–High	All scales	Precise root delivery
Subsurface Drip	90–95	40–55%	High	Medium–Large	Minimal evaporation
Smart IoT	95–97	35–50%	High	All scales	AI-driven automation

Source: Compiled from Camp (1998); EPA (2016); Lamm et al. (2021); Kumar et al. (2024)

CONCLUSION

Water-smart agriculture represents a critical pathway toward reconciling the competing demands of food security, economic development, and environmental sustainability in an era of escalating water scarcity. This review has demonstrated that the transition from conventional irrigation methods to advanced, technology-driven systems can yield substantial improvements in water use efficiency, crop productivity, and resource sustainability.

The evidence synthesized in this review indicates that modern irrigation technologies, particularly subsurface drip irrigation and IoT-based smart systems, can achieve water use efficiencies of 90–97%, compared to just 40–55% for traditional flood irrigation. IoT-integrated systems incorporating soil moisture sensors, weather data, AI algorithms, and cloud computing have demonstrated water savings of 35–50% while simultaneously increasing crop yields by up to 43% (Alwan et al., 2026). Smart irrigation controllers, as reported by the EPA (2016), can reduce outdoor water use by 20–50%, while research by Kumar et al. (2024) has achieved prediction accuracies of 98.7% through machine learning-based scheduling.

Complementary water conservation strategies, including deficit irrigation, mulching, rainwater harvesting, and precision

irrigation scheduling, provide additional layers of water savings when integrated with efficient irrigation hardware. The combination of these approaches—precision delivery technologies with data-driven decision-making—embodies the “more crop per drop” paradigm essential for sustainable agriculture.

However, several challenges impede widespread adoption, including high initial investment costs, limited technical expertise among smallholder farmers, inadequate infrastructure in developing regions, and the need for robust communication networks in rural areas. Future research should focus on developing cost-effective IoT solutions accessible to small-scale farmers, integrating renewable energy sources with smart irrigation systems, and exploring the role of nanotechnology and blockchain in water management. Government policies, subsidies, and incentive programmes will be essential in facilitating the transition to water-smart agriculture at scale.

As climate change intensifies and freshwater availability continues to decline globally, the adoption of water-smart agricultural technologies is not merely an option but an imperative. The convergence of precision agriculture, artificial intelligence, and IoT-enabled automation offers unprecedented opportunities to transform agricultural water management, ensuring food

security for a growing global population while preserving the planet's most vital natural resource.

Acknowledgement:

The authors thank all co-authors for their contributions and support in completing this manuscript.

Funding: NIL.

Conflict of Interest:

The authors declare no conflict of interest.

Author Contribution:

All authors reviewed, revised, and approved the final manuscript.

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