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Harnessing Smart Water Technologies for Resilient Fruit Production Under Changing Climates

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ABSTRACT

Climate change-induced water scarcity and erratic rainfall patterns pose critical threats to fruit production. This study explores the potential of Smart Water Management (SWM) technologies-such as precision irrigation, IoT-enabled soil moisture sensors, remote sensing, and decision support systems (DSS)-to enhance water use efficiency (WUE) and climate resilience in horticulture. Traditional irrigation methods operate at 30–40% WUE, whereas drip and micro-irrigation systems can achieve 80–90%, reducing water use by up to 40% and improving yield and fruit quality. Integration of AI-driven scheduling, GIS-based water zoning, and solar-powered pumps enables real-time, data-informed irrigation. Case studies from Indian orchards demonstrate 25–30% yield improvements with reduced groundwater use. Policy initiatives like PMKSY and public-private partnerships are vital for scaling adoption, particularly among smallholders. Despite challenges such as high initial costs and limited technical capacity, SWM offers a transformative pathway for sustainable, climate-smart fruit production.

Keywords: Smart Water Management, Precision Irrigation, Climate Resilience, Water Use Efficiency, IoT, Horticulture

1. INTRODUCTION

Agriculture today stands at a critical intersection of intensifying climate variability, water scarcity, and the pressing need for sustainable food production. Among all agricultural sectors, fruit farming is particularly susceptible to the consequences of climatic fluctuations due to its perennial nature, deep-rooted physiology, and sensitivity during phenological stages such as flowering, fruit set, and ripening. These vulnerabilities are exacerbated by shifting rainfall patterns, rising temperatures, and declining water tables, demanding a paradigm shift in water management practices.

Recent studies underscore a global rise in surface temperatures by approximately 1.1°C since the pre-industrial era (IPCC, 2023). In India, the 2023 monsoon season registered a 20%

rainfall deficit, which significantly curtailed horticultural productivity (IMD, 2023). Moreover, excessive and unregulated irrigation in traditional orchards has triggered rampant groundwater depletion. Alarmingly, over 90% of India’s extracted groundwater is allocated to irrigation (World Bank, 2024).

Smart Water Management (SWM) emerges as a pivotal component within the broader Climate-Smart Agriculture (CSA) framework. It encompasses precision irrigation, digital tools, remote sensing technologies, and data-driven decision support systems to optimize water use, enhance productivity, and build resilience against climate stress. In fruit farming, SWM is not merely an innovation but a necessity for future sustainability.

2. Water Requirements of Fruit Crops

Fruit crops have highly specific water demands which vary by species, age, and phenological stage. The following tables summarize average water requirements across major fruit crops:

Table 2.1: Seasonal Water Requirement of Selected Fruit Crops

Crop	Water Requirement (mm/year)
Banana	1200–2200
Citrus	900–1200
Grapes	500–1200
Pineapple	700–1000

Table 2.2: Daily Water Requirement Under Different Irrigation Methods

Crop	Drip (lit/plant/day)	Surface (lit/plant/day)
Coconut	75–100	200–300
Grapes	25–30	90–100
Mango	30–50	90–150
Guava	20–30	70–100
Sapota	20–30	70–100
Pomegranate	20–40	60–130
Banana	12–16	30–40
Citrus	10–20	25–65
Papaya	5–8	18–26

(Source: Reddy et al., 2010)

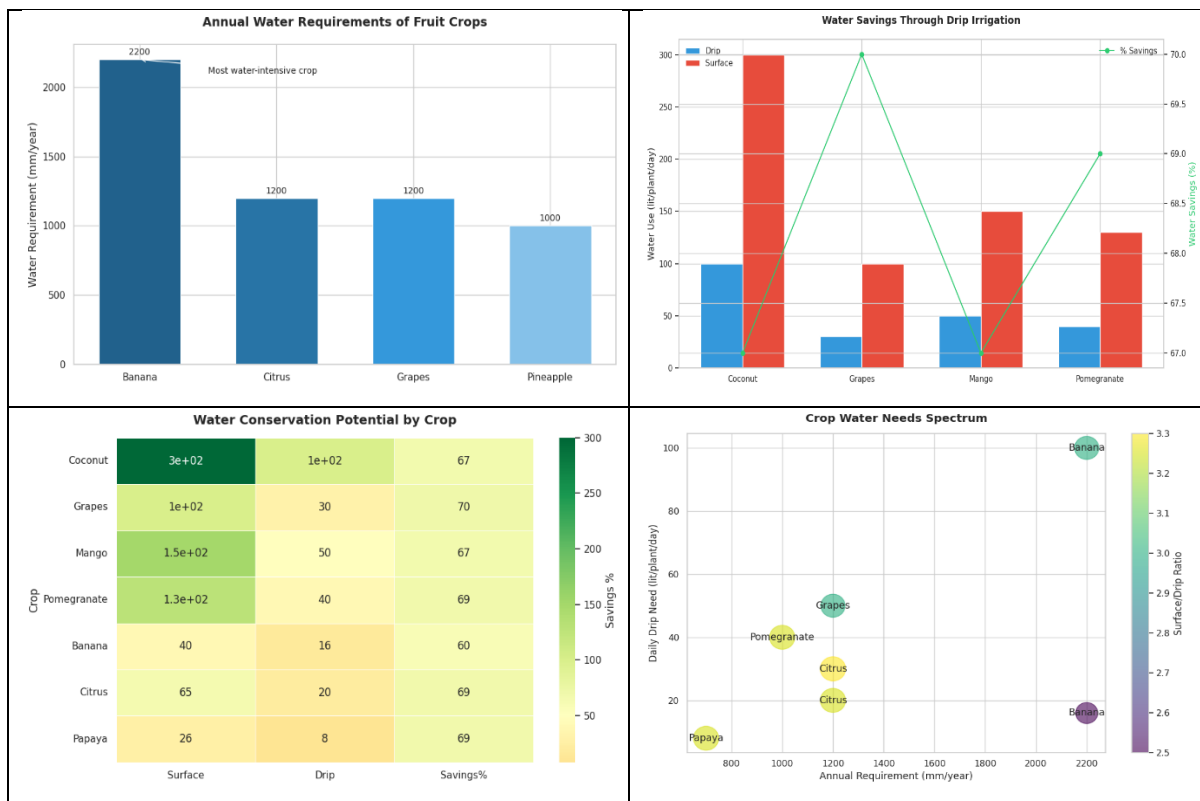


Figure 1: Comparative Water Requirements and Irrigation Efficiency of Major Fruit Crops

3. The Need for Smart Water Management in Fruit Farming

Fruit crops such as mango, citrus, pomegranate, banana, and grapes are among the most water-intensive horticultural commodities. Consistent and well-regulated water availability is essential across their phenological stages. Conventional irrigation methods such as surface and flood irrigation, still widely practiced, result in major inefficiencies. Studies have shown that surface methods deliver water use efficiency (WUE) as low as 30–40%, in contrast to 80–90% in drip or micro-irrigation systems (FAO, 2023).

Climate change further complicates irrigation planning by inducing erratic rainfall, intensifying evapotranspiration, and depleting groundwater. For instance, regions like Maharashtra and Karnataka report annual groundwater declines exceeding 1 meter in key horticulture belts (CGWB, 2024).

3.1 Key Drivers Necessitating SWM:

- (a) Seasonal Water Stress:** Drought during flowering and fruit set results in poor pollination, fruit drop, and low productivity.
- (b) Inefficient Practices:** Unscientific irrigation causes waterlogging, root suffocation, and disease outbreaks.
- (c) Soil Degradation:** Over-irrigation accelerates salinization, reducing soil fertility and orchard lifespan.

(d) Declining Water Productivity: Yield per unit water is decreasing; thus, efficiency is vital under resource constraints.

4. Principles of Smart Water Management

Smart Water Management (SWM) in fruit farming is grounded in a set of integrated principles that aim to balance productivity, sustainability, and resilience. These principles are especially crucial in the face of increasing climate variability, shrinking freshwater resources, and the growing demand for high-value horticultural produce.

4.1 Water Use Efficiency (WUE)

Water Use Efficiency refers to the maximization of crop output per unit of water consumed. In fruit farming, where water requirements are continuous and season-long, WUE is enhanced through:

- Adoption of micro-irrigation systems (e.g., drip, micro-sprinklers) that deliver water directly to the root zone, minimizing losses via evaporation, runoff, and percolation.
- Use of mulching and organic soil amendments to improve soil water retention.
- Integration of fertigation techniques to synchronize nutrient and water application, improving both inputs' efficiency.

Studies have shown that drip irrigation can improve WUE by 40–60% compared to conventional surface irrigation, particularly in water-intensive fruit crops such as banana, citrus, and pomegranate (ICAR-NRC, 2024).

4.2 Demand-Based Irrigation Scheduling

Instead of adhering to calendar-based watering, SWM emphasizes irrigation aligned with real-time crop water demand. This is achieved by:

- Monitoring soil moisture levels using TDR or capacitance sensors.
- Estimating crop evapotranspiration (ET_c) through meteorological data and crop coefficients (K_c).
- Using phenological stages (e.g., flowering, fruit set) as biological indicators to determine critical watering periods.

This approach minimizes both under-irrigation (leading to drought stress) and over-irrigation (causing waterlogging and nutrient leaching), ensuring optimal physiological performance and fruit quality.

4.3 Technology Integration

SWM is enabled by a suite of modern technologies that bring precision, automation, and scalability to irrigation management. Key innovations include:

- **IoT-based Smart Irrigation Systems:** These include sensors, automated valves, and cloud platforms that allow real-time remote irrigation control and scheduling.

- **GIS and Remote Sensing:** Geospatial technologies support spatial variability assessment in orchards, identifying water-stressed zones and enabling site-specific management.
- **Mobile Apps and Field Controllers:** Farmers receive real-time alerts and actionable insights via mobile interfaces, enabling decentralized and inclusive water management.

These tools empower even smallholder farmers to adopt precision agriculture principles.



Figure 2: Smart Water Management Technologies for Climate-Resilient Fruit Farming

4.4 Data-Driven Decision-Making

Smart Water Management transitions farmers from intuition-based practices to scientifically-informed irrigation strategies. This involves:

- Utilizing Decision Support Systems (DSS) like **AquaCrop**, **CROPWAT**, and **Irrisat** to simulate crop-water relationships and predict water needs under different scenarios.
- Leveraging historical and real-time data from weather stations, soil moisture probes, and crop growth models to adjust irrigation plans dynamically.
- Incorporating AI/ML algorithms for predictive modeling of drought events, optimal irrigation timing, and water budgeting.

This principle ensures that every irrigation decision is grounded in empirical data, leading to increased efficiency and yield stability.

4.5 Sustainability and Equity

Sustainability in SWM encompasses the preservation of water resources, soil health, and energy inputs over the long term, while equity ensures that benefits are accessible across socio-economic strata. This principle is actualized by:

- Promoting decentralized water sources such as rainwater harvesting structures, check dams, and on-farm ponds to reduce aquifer pressure.
- Encouraging water-conserving crop choices and intercropping systems that optimize land and water use.
- Providing government subsidies, training, and ICT access to smallholders through schemes like **Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)**.
- Integrating gender-sensitive and inclusive approaches to ensure that women and marginalized communities also benefit from smart irrigation interventions.

5. Smart Water Technologies in Fruit Farming

5.1 Drip and Micro-Irrigation Systems

Drip and micro-irrigation are among the most efficient irrigation methods currently available for fruit crops. These systems deliver water directly to the root zone through a network of tubes, pipes, and emitters operating at low pressure. By localizing water application, they minimize evaporation losses and deep percolation beyond the root zone, ensuring higher water use efficiency (WUE).

For example, in pomegranate orchards, adoption of drip irrigation has been shown to reduce overall water consumption by up to 40%, while simultaneously increasing fruit yield by approximately 30%, according to recent findings by ICAR-National Research Centre on Pomegranate (2024). This dual benefit results from more uniform water distribution and precise control over irrigation timing and quantity.

5.2 Soil Moisture Monitoring Technologies

Precise irrigation scheduling relies on accurate knowledge of soil moisture status. Sensors such as capacitance probes and Time Domain Reflectometry (TDR) devices measure the volumetric water content of the soil in real time. Meanwhile, tensiometers measure the matric potential, which reflects the energy plants expend to extract water from the soil. These complementary measurements help farmers avoid under-irrigation (leading to water stress) or over-irrigation (leading to waterlogging and nutrient leaching).

By integrating these sensors into automated or manual irrigation management, fruit growers can optimize water application schedules and volumes, improving water productivity and crop health.

5.3 Remote Sensing and Geographic Information Systems (GIS)

Advanced remote sensing tools enable monitoring of crop water status at a large scale with high spatial resolution. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) provide information on crop vigor, while thermal imaging identifies canopy temperature variations

linked to water stress. Models estimating crop evapotranspiration (ET) based on meteorological data further support irrigation decisions.

Using GIS, orchard managers can create detailed spatial maps that delineate zones with varying soil types, topography, and water needs. This spatial information supports differential irrigation, applying more water to stressed zones and less to well-irrigated areas, thus enhancing overall water use efficiency.

5.4 Decision Support Systems (DSS)

Decision Support Systems like AquaCrop (developed by FAO) and CROPWAT offer simulation models that combine climate data, crop parameters, and soil characteristics to predict crop water requirements throughout the growing season. These tools provide farmers with customized irrigation scheduling recommendations tailored to local conditions, helping avoid guesswork and optimize resource use.

DSS can also incorporate weather forecasts and climate change scenarios to improve resilience planning in fruit farming systems.

5.5 Rainwater Harvesting and Farm Ponds

Harvesting rainwater is a sustainable strategy to augment irrigation water availability, especially during dry periods. Techniques include rooftop rainwater harvesting, where water is collected and stored in lined tanks, and surface runoff harvesting in farm ponds and percolation pits that recharge groundwater aquifers.

Such systems reduce reliance on erratic groundwater supplies and help maintain moisture availability for fruit crops, contributing to climate-smart agriculture.

5.6 Solar-Powered Water Pumps

The use of solar photovoltaic (PV) pumps for irrigation is gaining momentum, particularly in off-grid or remote farming areas. Solar-powered pumps eliminate dependence on fossil fuels and grid electricity, significantly reducing operational costs and carbon footprint.

In India, more than 300,000 solar pump units are installed, supported by government programs under the Ministry of New and Renewable Energy (MNRE, 2024). These pumps provide a clean, renewable energy source for efficient water lifting and delivery in fruit orchards, enabling sustainable irrigation practices



Figure 3: Smart Water Management Technologies for Climate-Resilient Fruit Farming

6. Climate-Smart Impacts of Smart Water Management (SWM)

6.1 Drought Resilience:

Smart irrigation systems help fruit orchards withstand prolonged dry spells and heat waves by maintaining optimal soil moisture and reducing crop water stress. This buffering capacity can minimize climate-induced yield losses and stabilize production.

6.2 Greenhouse Gas (GHG) Emission Reduction:

Low-energy systems such as drip irrigation combined with solar-powered pumps reduce fossil fuel use and associated greenhouse gas emissions, contributing to climate change mitigation efforts in agriculture.

6.3 Improved Fruit Quality:

Consistent and optimized soil moisture enhances physiological processes in fruit crops, promoting better sugar accumulation, colour development, texture, and shelf-life. This improves marketability and profitability.

6.4 Aquifer Sustainability:

By shifting irrigation from flood or sprinkler methods to scheduled, need-based watering, groundwater extraction can be minimized. Coupled with recharge from rainwater harvesting, this sustains aquifer health and long-term water availability.

7. Policy and Institutional Support for SWM in Fruit Farming

7.1 Government Schemes:

Initiatives such as the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) offer financial subsidies and technical support for adopting micro-irrigation systems, encouraging farmers to switch to water-efficient technologies.

7.2 Extension Services:

Krishi Vigyan Kendras (KVKs), agricultural universities, and mobile advisory apps provide training, demonstrations, and timely information dissemination about smart irrigation practices to farmers.

7.3 Public-Private Partnerships (PPP):

Collaborations between agritech companies, cooperatives, and government agencies enable delivery of bundled solutions combining hardware (e.g., sensors, pumps) and advisory services, making smart water technologies more accessible.

7.4 Research and Development:

Institutions like ICAR and state agricultural universities continuously develop crop-specific irrigation guidelines, sensor calibration standards, and decision models tailored to local fruit crops and climatic conditions.

8. Challenges and Future Outlook

8.1 Barriers:

The initial capital investment required for automated drip systems, sensors, and solar pumps is often prohibitive for smallholder farmers.

Lack of awareness, technical training, and trust in new technologies limits adoption.

The value chain for smart water management tools is fragmented, with limited integration among manufacturers, service providers, and end-users.

8.2 Opportunities:

Subsidies on sensor kits and mobile-based irrigation advisory platforms can lower entry barriers for small farmers.

Emerging AI and machine learning-integrated water management platforms offer real-time irrigation recommendations based on weather, soil, and crop data.

Development of community-level shared smart irrigation infrastructure could reduce costs and promote knowledge exchange.

9. CONCLUSION

Smart Water Management (SWM) in fruit farming is a vital, forward-looking approach to overcoming the dual challenges of water scarcity and climate variability that threaten agricultural productivity and sustainability. By employing advanced technologies such as drip and micro-

irrigation, soil moisture sensors, remote sensing, decision support tools, and solar-powered pumps, SWM enables precise, efficient, and timely irrigation tailored to crop needs. This leads to significant water savings—often up to 40%—while simultaneously improving fruit yield and quality, including attributes like sugar content, texture, and shelf life. In addition to boosting productivity, SWM plays a crucial role in conserving groundwater resources and reducing the carbon footprint of irrigation practices, supporting broader climate change mitigation efforts. For countries like India, where horticulture supports millions of livelihoods and water resources are increasingly stressed, widespread adoption of SWM can enhance drought resilience, stabilize incomes, and improve food security.

With strong policy backing, extension support, and public-private partnerships, SWM offers a sustainable pathway to a climate-resilient, water-secure, and farmer-friendly horticultural future. Ultimately, it balances economic viability with environmental stewardship, ensuring fruit farming remains productive and sustainable amid growing climatic and resource challenges.

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