

Original Research Article

Smart Irrigation Scheduling Improves Water Productivity and Crop Yield under Water-Limited Conditions: Precision Water Management, Predictive Analytics, Climate-Smart Adaptation, and Yield Stability

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Abstract

Growing competition for freshwater, increasing evapotranspiration, irregular rainfall and recurrent drought are transforming irrigation scheduling from a routine farm operation into a central component of climate-resilient crop production. Smart irrigation scheduling integrates soil, plant, weather and crop information to determine when irrigation should be applied, how much water should be supplied and where water is most needed. This review synthesizes the physiological, agronomic and technological basis through which smart irrigation scheduling improves water productivity and sustains crop yield under water-limited conditions. Conventional calendar-based irrigation frequently fails to account for spatial and temporal variability in soil moisture, atmospheric demand and crop developmental sensitivity, resulting in over-irrigation, deep percolation, nutrient loss or avoidable water stress. In contrast, soil-moisture sensors, evapotranspiration-based scheduling, canopy-temperature measurements, remote sensing, Internet of Things platforms, decision-support systems, artificial intelligence and machine-learning models allow irrigation to respond dynamically to actual crop and environmental conditions. Smart scheduling improves productivity principally by maintaining root-zone water within physiologically acceptable limits, reducing non-beneficial water losses, protecting flowering and reproductive development, improving nutrient uptake and coordinating controlled water deficits with crop tolerance. Its effectiveness, however, depends strongly on crop type, genotype, phenological stage, root-zone characteristics, irrigation method, sensor calibration, weather variability and economic feasibility. The plant microbiome, stress-responsive genetic traits, hormonal regulation and soil biological properties add further complexity because they influence root water acquisition and crop tolerance to intermittent soil drying. Evidence from smart horticulture and precision-agriculture studies increasingly supports integration of IoT sensors, artificial intelligence, crop models and climate forecasts into adaptive irrigation systems. Future irrigation management should move from fixed water application toward predictive, closed-loop and plant-responsive scheduling capable of distinguishing beneficial water conservation from yield-threatening stress. Such integration offers a practical pathway for increasing crop water productivity, stabilizing yield and conserving scarce freshwater under increasingly water-limited production environments.

Keywords: smart irrigation; irrigation scheduling; water productivity; soil-moisture sensor; evapotranspiration; Internet of Things; artificial intelligence.

Highlights

- Smart irrigation scheduling applies water according to crop demand rather than predetermined calendar intervals [1–6].
- Soil-water sensors, plant indicators, weather information and evapotranspiration estimates provide complementary information for irrigation decisions [1,5–8].
- Sensor-guided irrigation can substantially reduce irrigation-water use while maintaining or improving yield [7,8].
- Artificial intelligence, IoT and DSS enable real-time, predictive and site-specific irrigation management [9–13,34,50].
- Smart scheduling is particularly valuable under drought, heat and irregular rainfall because irrigation thresholds can be modified according to atmospheric demand [14–18,33].
- Biological stress tolerance, root architecture, hormonal regulation and rhizosphere functioning influence crop response to water-saving irrigation [35,36,39,46–48].

1. Introduction

Agriculture is the dominant consumptive user of freshwater in many regions, and increasing competition among agricultural, domestic, industrial and environmental sectors has intensified pressure to produce more crop yield per unit of water supplied [1–4]. Climate change further complicates this challenge through increasing temperatures, irregular precipitation, higher atmospheric evaporative demand and more frequent drought and heat episodes [14–18]. These changes are particularly important in irrigated agriculture because the timing of water supply can be as influential as total seasonal irrigation.

Traditional irrigation scheduling commonly relies on fixed calendars, farmer experience or predetermined irrigation intervals. Such approaches can work under stable production environments but may become inefficient when soil properties, weather conditions and crop development vary over time. Irrigation supplied too early can increase evaporation, runoff, deep drainage and nutrient leaching, whereas delayed irrigation can reduce stomatal conductance, photosynthesis, cell expansion, reproductive development and final yield [2–6].

Smart irrigation scheduling attempts to overcome these limitations by answering three interconnected questions: when to irrigate, how much to irrigate and where irrigation is required. Decisions are derived from measurements or predictions of soil-water availability,

evapotranspiration, crop developmental stage, plant stress, weather and expected rainfall [1,5–13].

FAO evapotranspiration methodology established a widely used framework in which reference evapotranspiration (ET_0) is adjusted by crop coefficients to estimate crop evapotranspiration (ET_c) [1]. Modern scheduling expands this framework by combining ET estimates with soil sensors, canopy measurements, remote sensing, weather forecasts and automated controllers.

Systematic evaluation of soil-water sensors indicates that sensor-guided scheduling frequently uses less irrigation water while maintaining or even improving crop yield compared with conventional scheduling [7]. Emerging intelligent irrigation approaches similarly combine IoT, artificial intelligence and predictive modelling to account for field hydrological, climatic and crop characteristics [8–13].

The significance of smart scheduling increases under water-limited conditions. When available irrigation cannot fully satisfy crop evapotranspiration, management must distribute limited water among growth stages in a way that maximizes economic yield or water productivity. Under such conditions, indiscriminate reduction in irrigation is less effective than strategically timed water restriction [3,4,19–23].

The attached literature further supports this multidimensional interpretation. Climate-smart horticultural systems emphasize efficient irrigation, soil-water conservation, protected cultivation and digital technologies as complementary strategies for resource-efficient crop production [44]. Precision-horticulture systems use sensors and real-time data to identify soil-moisture variability and tailor inputs according to crop demand [50].

Smart irrigation should therefore be understood not as a particular sensor or controller but as an integrated decision framework connecting soil, plant, atmosphere and management. This review examines the mechanisms by which such scheduling affects water productivity and crop yield, the major technological approaches available, the interaction with water deficit and climate variability, and future opportunities for AI-enabled irrigation.

2. Conceptual Basis of Smart Irrigation Scheduling

Irrigation scheduling is the process of determining irrigation timing and application depth to maintain crop water status within a desirable range. Smart scheduling differs from conventional scheduling by continuously

or periodically updating irrigation decisions using measured, modelled or forecast information [5–13].

An effective smart-irrigation system normally contains four functional components. The first is **sensing**, which measures soil, plant or atmospheric variables. The second is **data transmission and storage**, commonly achieved through IoT networks and cloud platforms. The third is **decision analysis**, using threshold rules, crop models, DSS or machine learning. The fourth is **actuation**, whereby irrigation valves, pumps or variable-rate irrigation systems execute the recommended water application [9–13,34,50].

The simplest smart controller may switch irrigation on when volumetric soil-water content falls below a pre-defined threshold. More advanced systems integrate soil moisture with ETc, rainfall forecasts, phenological stage and expected atmospheric demand. Closed-loop systems subsequently evaluate the effect of irrigation and adjust future applications accordingly.

This feedback structure distinguishes smart irrigation from fixed irrigation programming. Rather than assuming crop water demand, it continually estimates whether the root zone is approaching a physiologically important threshold.

2.1 Irrigation amount versus irrigation timing

Seasonal irrigation volume alone does not determine crop response. Two fields receiving identical amounts of water can produce substantially different yields if the timing of irrigation differs [3,4,19–23].

Water supplied during periods of low crop demand may be lost through drainage, whereas the same quantity applied around flowering or reproductive development may prevent substantial yield loss. Consequently, smart scheduling seeks to maximize the **marginal crop benefit per unit of irrigation water**.

2.2 Water productivity as the operational target

Water productivity can be expressed as crop yield per unit of water consumed or supplied. Depending on the purpose, denominators may include evapotranspiration, irrigation water, or total water input. Improvements in water productivity therefore arise either by producing more yield with similar water consumption or by maintaining acceptable yield with lower water use [3,4,19–23].

Under water-limited conditions, maximizing absolute yield and maximizing water productivity are not always identical objectives. Extremely conservative irrigation may generate high water productivity while significantly reducing total yield. Smart scheduling

must therefore balance water conservation with economically acceptable production.

3. Information Sources for Smart Irrigation Decisions

3.1 Soil-Moisture-Based Scheduling

Soil-water monitoring provides one of the most direct approaches to determining whether sufficient water remains within the crop root zone. Technologies include tensiometers, capacitance probes, frequency-domain reflectometry, time-domain reflectometry, resistance-based sensors and matric-potential sensors [5–8].

Sensor placement is crucial because soil-water distribution varies vertically and horizontally. Shallow sensors can indicate depletion in the active surface root zone, whereas deeper sensors can identify whether irrigation is penetrating below effective rooting depth.

A systematic review of soil-water sensors reported that sensor-guided scheduling generally reduced water application relative to conventional scheduling while achieving similar or higher yield [7]. Such evidence supports soil moisture as a useful foundation for smart irrigation, although calibration and installation errors remain important.

3.2 Evapotranspiration-Based Scheduling

ET-based scheduling estimates the volume of water lost through soil evaporation and plant transpiration. Reference evapotranspiration calculated from weather variables is multiplied by crop coefficients to estimate crop water demand [1].

ET scheduling has several strengths. It directly connects water application to atmospheric demand, can operate at large spatial scales and is compatible with weather stations and forecasts. However, crop coefficients vary with variety, canopy development, soil evaporation, planting density and management conditions.

Smart systems can update Kc values using remote sensing or canopy development, improving upon static tabulated coefficients.

3.3 Plant-Based Indicators

Plants integrate the combined effects of soil-water availability and atmospheric demand. Plant-based scheduling therefore provides valuable information that soil sensors alone may not capture [5,6].

Useful indicators include:

- leaf or stem water potential;
- stomatal conductance;
- sap flow;

- canopy temperature;
- crop water stress index;
- leaf expansion;
- spectral reflectance.

Canopy temperature is especially attractive because declining transpiration generally increases leaf temperature. Thermal cameras mounted on ground platforms, UAVs or satellites can therefore identify areas experiencing water stress.

3.4 Weather Forecasting

Short-range forecasts of rainfall, temperature, solar radiation, humidity and wind can prevent unnecessary irrigation immediately before rainfall or allow additional irrigation ahead of severe heat.

This predictive capability is increasingly important because climate variability makes historical irrigation schedules unreliable [14–18,33,34,44].

4. Internet of Things and Automated Irrigation

The Internet of Things has transformed irrigation automation by linking distributed field sensors with controllers, mobile devices and cloud-based platforms [9–13,34,50].

IoT-enabled systems continuously measure root-zone soil moisture, temperature, relative humidity and other environmental conditions. Measurements are transmitted to software platforms, where predefined thresholds or predictive algorithms determine whether irrigation is necessary.

The attached precision-horticulture study specifically describes IoT irrigation systems that monitor soil-water status continuously and deliver water only when required, reducing unnecessary water application and allowing remote control [50].

Similarly, the DSS article describes sensor networks collecting soil moisture, temperature, humidity and crop-growth information and transmitting these data for dynamic irrigation recommendations [34].

Automation has several advantages under water-limited conditions. Short irrigation pulses can be delivered precisely when depletion thresholds are reached, avoiding both severe stress and over-irrigation. Automation is also particularly suitable for drip and micro-irrigation because application depth can be accurately controlled.

However, automation cannot compensate for incorrect thresholds. A poorly calibrated sensor connected to an automatic valve can repeatedly make an incorrect irrigation decision. Smart irrigation therefore requires

agronomic intelligence in addition to technological connectivity.

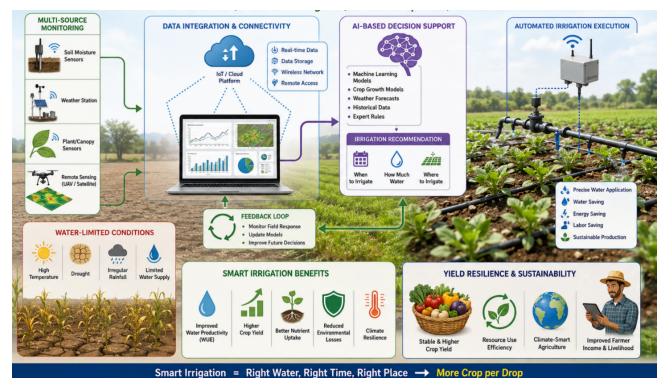


Figure 1. Smart Irrigation Scheduling Improves Water Productivity and Crop Yield

5. Artificial Intelligence, Machine Learning and Decision-Support Systems

Artificial intelligence expands irrigation scheduling beyond simple threshold control. Machine-learning models can analyse nonlinear relationships among soil moisture, temperature, humidity, rainfall, crop stage, canopy response, irrigation history and yield [9–13,34].

Decision-support systems integrate such data with crop simulation models and management rules. The attached DSS paper describes integration of soil properties, climatic conditions, crop requirements and forecasts to optimize irrigation scheduling and improve resource-use efficiency [34].

Machine learning is especially useful where irrigation response depends on interacting factors. For example, a soil-moisture value of 20% may represent adequate supply on one soil but severe depletion on another. The crop response may differ further according to root depth, VPD and growth stage.

AI models can potentially learn these interactions and predict irrigation requirement directly.

The attached machine-learning and multispectral-imaging review, although focused on plant disease detection, demonstrates the capacity of SVM, Random Forest, CNN and transformer architectures to interpret complex spectral and physiological crop signals [37]. Multispectral sensing can detect changes in chlorophyll, tissue water relations and cellular condition before visible symptoms develop. These same analytical approaches have considerable potential for irrigation stress classification.

Remote sensing and AI should therefore be viewed as enabling technologies for plant-responsive irrigation rather than merely as monitoring tools.

Table 1. Major approaches used in smart irrigation scheduling

Scheduling approach	Primary information	Major advantage	Major limitation	Smart-irrigation application
Soil moisture	Volumetric water content/root-zone depletion	Direct assessment of stored water	Sensor placement and calibration	Threshold-triggered irrigation
Soil matric potential	Soil-water tension	Closely linked with water availability	Soil-specific interpretation	Irrigation onset threshold
ET-based	$ET_0 \times K_c$	Quantifies atmospheric crop demand	Depends on accurate K_c and weather data	Daily irrigation replacement
Plant water potential	Leaf/stem water status	Direct physiological indicator	Labour-intensive measurements	Stress-threshold scheduling
Canopy temperature	Thermal response	Rapid and spatially scalable	Strongly affected by weather	Thermal stress detection
Remote sensing	Thermal/multispectral indices	Field-scale spatial coverage	Resolution/cloud constraints	Variable-rate irrigation
Weather forecast	Rainfall, VPD and temperature	Predictive rather than reactive	Forecast uncertainty	Delay or advance irrigation
IoT + DSS	Multi-sensor information	Real-time integrated decisions	Connectivity and infrastructure	Automated smart irrigation
AI/ML	Historical + real-time multidimensional data	Detects complex nonlinear relationships	Training data and transferability	Predictive irrigation scheduling

6. Why Smart Scheduling Improves Water Productivity

Smart irrigation increases water productivity through several complementary mechanisms.

6.1 Reduction of non-beneficial water losses

Applying water according to root-zone demand reduces runoff, deep percolation and unnecessary soil evaporation. Drip and micro-irrigation further concentrate water around the active root system [3,4,44].

Climate-smart horticultural research emphasizes that drip and micro-irrigation reduce evaporation, runoff and deep-percolation losses while improving water-use efficiency [44].

6.2 Avoidance of over-irrigation

Over-irrigation can reduce oxygen availability in the root zone, increase nutrient leaching and promote unnecessary vegetative growth. Smart scheduling limits water application after the target soil-water status is restored.

6.3 Prevention of damaging water stress

Yield loss often accelerates once crop water status crosses a critical physiological threshold. Smart sensors enable irrigation before this threshold is exceeded.

6.4 Strategic use of controlled deficit

Where full irrigation is impossible, smart scheduling allows water deficit to be placed during relatively tol-

erant crop stages while protecting sensitive periods [3,4,19–23].

Meta-analytical evidence shows that deficit irrigation frequently raises water productivity but produces context-dependent yield penalties. Wheat, vegetables and other crops exhibit large variation according to irrigation level, timing, soil and climatic conditions [19–23].

Recent meta-analysis further indicates that moderate deficit irrigation can maintain yield much more successfully than severe deficit irrigation, reinforcing the importance of threshold selection rather than indiscriminate water reduction [23].

7. Smart Irrigation and Crop Yield Formation

Maintaining yield under water limitation requires coordination between irrigation and crop phenology.

7.1 Vegetative growth

Moderate soil-water deficits during early vegetative development may reduce excessive leaf area and transpiration without substantially affecting final yield in some crops. Severe stress, however, limits cell division, cell expansion and canopy establishment [14–18].

7.2 Flowering and reproductive development

Flowering is often one of the most drought-sensitive crop stages. Water deficit can reduce pollen viability, fertilization, flower retention and seed or fruit set [16–18,33,47].

The attached review on hormonal regulation of reproductive development highlights the coordinated role of auxin, gibberellins, cytokinins, ABA, ethylene, brassinosteroids, jasmonates and salicylic acid in flowering, fertilization, fruit set and seed development [47].

Smart irrigation can therefore protect reproductive processes by prioritizing water during these critical stages.

7.3 Grain and fruit filling

Water stress during filling can shorten assimilate accumulation, accelerate senescence and reduce final grain or fruit size. In horticultural crops, water availability can also affect soluble solids, texture, nutrient concentration and market quality.

Consequently, scheduling should incorporate both yield quantity and quality targets.

8. Water-Limited Conditions, Heat and Climatic Variability

A fixed soil-moisture threshold does not always produce the same plant response. The severity of a given soil-water deficit changes with atmospheric evaporative demand.

High temperature and high VPD increase transpiration demand, causing leaf water potential to decline rapidly. During combined heat and drought, plants experience reductions in photosynthesis, water relations and reproductive performance that may be greater than under either stress alone [33].

The attached heat–drought review reports that simultaneous stress disrupts photosynthesis, nutrient uptake and reproductive development, enhances oxidative stress and modifies hormonal balance [33].

Smart scheduling should therefore adopt climate-responsive thresholds. During a heat wave, irrigation may need to be triggered at a higher soil-moisture level than during mild weather. Conversely, irrigation can be delayed when rainfall is highly probable.

This approach changes irrigation management from **reactive replacement of depleted soil water** to **anticipatory management of crop stress risk**.

The climate-resilient horticulture literature similarly emphasizes drought, heat and combined stress as major threats to crop performance and identifies WUE, root architecture and maintenance of reproductive development as important adaptive traits [43].

9. Crop-Specific Responses

Smart irrigation principles are broadly applicable, but threshold values cannot be universally transferred

across crops.

9.1 Cereals

Wheat and maize are major targets for irrigation optimization because large areas are produced under limited water.

In wheat, moderate deficit irrigation can increase WUE, but the outcome depends on irrigation level, timing, precipitation and soil properties [20].

Maize is particularly sensitive around tasselling, silking and early kernel establishment. Smart scheduling should prioritize these reproductive periods when seasonal water is limited.

9.2 Vegetable crops

Vegetable yield and quality respond rapidly to root-zone water status. A global meta-analysis demonstrates that water-productivity benefits of deficit irrigation depend strongly on crop species, soil texture and production environment [21].

Tomato is particularly useful for smart irrigation research because fruit yield, size and quality respond to both irrigation amount and environmental conditions.

The attached tomato experiment demonstrates strong genotype × sowing-window interactions affecting crop yield under changing weather and disease environments [31]. The broader implication is that irrigation scheduling cannot be separated completely from crop genotype and seasonal environment. Weather conditions such as temperature, rainfall and humidity influenced crop performance in that study.

9.3 Fruit crops

Fruit crops require multi-season management and often have deep perennial root systems. Smart irrigation can support regulated deficit strategies, but water restriction must consider flowering, fruit set, rapid fruit enlargement and return bloom.

Genetic and molecular differences among fruit crops further influence tolerance to drought, heat and salinity [46].

9.4 Protected horticulture

Greenhouses and protected structures are particularly suited to smart irrigation because both crop environment and fertigation can be tightly regulated [44,50].

The climate-smart horticulture article notes that irrigation and fertigation can be precisely controlled under protected systems, increasing overall resource efficiency [44].

Table 2. Major mechanisms through which smart irrigation influences crop water productivity and yield

Smart scheduling function	Immediate effect	Plant/crop consequence	Expected production benefit
Irrigation before critical depletion	Maintains root-zone water supply	Prevents severe stomatal closure and photosynthetic decline	Higher biomass and yield
Reduced unnecessary irrigation	Limits deep drainage and runoff	Improves proportion of applied water used by crop	Higher irrigation water productivity
Stage-specific irrigation	Protects flowering and grain/fruit set	Maintains reproductive success	Greater harvestable yield
ET-based adjustment	Matches water supply with atmospheric demand	Reduces under- and over-irrigation	Stable crop water status
Weather forecast integration	Anticipates rain and heat	Avoids unnecessary irrigation and severe heat stress	Water saving and yield protection
Sensor + drip irrigation	Delivers precise root-zone water	Improves water and nutrient acquisition	Increased WUE and nutrient-use efficiency
Variable-rate irrigation	Responds to spatial field variability	Reduces wet and dry zones	Improved uniformity and yield
AI prediction	Anticipates crop demand	Enables proactive rather than reactive irrigation	Greater yield stability
Controlled deficit irrigation	Conserves water during tolerant stages	Allocates saved water to critical stages	Improved seasonal water productivity

10. Root Biology, Microbiomes and Smart Irrigation

The response of a crop to irrigation depends not only on physical soil moisture but also on root architecture and biological activity in the rhizosphere.

Beneficial soil microorganisms can modify root growth, nutrient acquisition, hormone signalling, osmotic adjustment and antioxidant defence [35,36,39].

The attached functional-profiling review identifies PGPR, mycorrhizal fungi and endophytes as contributors to drought and other stress tolerance through phytohormone modulation, osmolyte accumulation and antioxidant activation [35].

Rhizosphere microbiome restructuring can similarly influence root architecture, nutrient cycling and stress resilience [36].

Endophytes provide an additional internal mechanism by modifying plant hormone signalling, redox regulation and root development [39].

This has important implications for smart irrigation. Two crops experiencing the same soil moisture may differ in effective water uptake because of root architecture, mycorrhizal association or microbial effects on root physiology.

Future smart-irrigation models could therefore incorporate indicators of root-zone biological functioning rather than treating soil simply as a physical water reservoir.

The attached metagenomic analysis also emphasizes that management practices alter microbial diversity,

functional genes and ecological resilience [38]. Metagenomics may ultimately help identify microbiome states associated with improved crop performance under repeated drying and rewetting.

11. Genetic and Molecular Traits Influencing Irrigation Response

Smart irrigation cannot completely eliminate water stress. Crop genetic capacity therefore remains important.

Traits relevant to smart scheduling include:

- deep and proliferative rooting;
- rapid stomatal regulation;
- osmotic adjustment;
- antioxidant capacity;
- reproductive stability;
- rapid recovery after rewatering;
- tolerance to combined drought and heat.

The attached climate-resilient horticultural review highlights breeding for WUE, root architecture and reproductive stability under drought [43]. Molecular and genomic approaches including DREB, WRKY and NAC transcription factors are proposed as tools for stress-resilient crop development.

The genetic and molecular review of fruit crops similarly identifies WRKY, NAC, MYB, bZIP and DREB factors and hormone-mediated signalling as important regulators of stress adaptation [46].

WRKY-mediated stress-response networks are also relevant because irrigation mismanagement can aggra-

vate salinity in irrigated soils. The attached salt-stress article specifically links salinization to irrigation mismanagement and describes WRKY involvement in ion homeostasis, antioxidant defence and stress signalling [48].

The future objective should therefore be genotype-specific irrigation scheduling, where thresholds are adjusted according to cultivar water-use strategy and stress tolerance.

12. Smart Irrigation within a Wider Climate-Smart Production System

Irrigation cannot be optimized independently of other crop-management practices.

Nutrient supply influences root growth and water uptake. Integrated nutrient management in banana demonstrated large improvements in productivity and farmer-level performance under field conditions [32]. Although the study did not specifically investigate smart irrigation, it illustrates the importance of synchronizing resource-management technologies rather than optimizing a single input in isolation.

Likewise, the commercial marigold technology-assessment study demonstrates that field productivity depends not only on technical effectiveness but also on farmer adoption, extension support, timely input availability and local implementation [40].

Precision irrigation should therefore increasingly be integrated with precision nutrient management, crop protection and climate-adaptive management.

Biofortification research also highlights the role of agronomic nutrient management, microbial interventions and precision-agriculture tools in improving nutrient uptake and nutritional quality [42]. This provides an important reminder that irrigation influences not only yield but also nutrient transport and produce quality.

13. Additional Horticultural Interfaces Relevant to Smart Water Management

Some of the attached articles address production processes that are not directly irrigation-focused. They nevertheless illustrate why irrigation must ultimately be incorporated into whole-system horticultural management rather than treated independently.

Micropropagation and in vitro technologies enable rapid production of uniform planting material [41]. Uniform crop establishment can improve the predictability of crop water demand, although the uploaded article itself does not test irrigation scheduling.

Pollination technologies provide another example. The sonic and vibrational pollination review demonstrates that fruit set and yield depend strongly on effective reproductive processes and that automation and AI can be integrated into protected horticultural systems [45]. Smart irrigation and smart pollination are therefore complementary rather than competing forms of automation in controlled-environment horticulture.

Growing-media properties also influence water management. Peat-based substrates possess high water-holding capacity but interact with irrigation and fertilization and have important carbon and greenhouse-gas implications [49]. Substrate-specific irrigation thresholds will therefore be essential in container and protected horticulture.

These examples broaden smart irrigation into smart production-system management, where water interacts with substrate, nutrient, pollination, genotype, climate and crop-quality processes.

14. Translating Smart Irrigation from Research to Farmers' Fields

Technical effectiveness does not ensure adoption. Smart irrigation systems can involve soil probes, controllers, communication networks, weather stations and subscription-based software, creating barriers for resource-constrained farms.

The climate-smart horticulture literature identifies high investment requirements for drip irrigation and precision tools as important constraints to adoption [44].

Farmer adoption is more likely when technologies demonstrate:

- measurable irrigation-water savings;
- stable or increased crop yield;
- low operating complexity;
- clear economic returns;
- reliable technical support;
- compatibility with existing pumps and irrigation systems.

The banana field study demonstrates how demonstrations and farmer–scientist interaction can accelerate adoption of improved resource-management technology [32]. The marigold study similarly demonstrates that extension gaps can remain substantial even when the underlying technology is agronomically feasible [40].

Smart irrigation development should therefore include participatory trials, farmer training and economic analysis from the beginning rather than after technical development is complete.

15. Research Gaps and Future Priorities

First, irrigation studies require standardized reporting. Soil texture, rooting depth, sensor placement, calibration, irrigation threshold, ET methodology, crop stage, weather, rainfall, irrigation amount and final water productivity should all be documented.

Second, research should move from single sensors toward sensor fusion. Soil moisture, canopy temperature, VPD and weather forecasts together provide a more reliable assessment of irrigation need than any variable alone.

Third, AI models require greater field validation. Algorithms trained in one crop, soil or climate may perform poorly when transferred to another environment.

Fourth, smart irrigation should become more predictive. Future systems should anticipate soil-water depletion, rainfall and heat stress rather than waiting until a threshold has already been exceeded.

Fifth, crop-stage sensitivity should be incorporated explicitly into irrigation algorithms. A single fixed soil-moisture threshold throughout the season ignores major differences between vegetative and reproductive water requirements.

Sixth, genotype-specific scheduling requires investigation. Climate-resilient breeding and high-throughput phenotyping are generating cultivars with different root systems, stomatal behaviour and stress tolerance [43,46]. Their irrigation thresholds may therefore differ.

Seventh, microbiome-irrigation interactions deserve greater attention. Soil drying and rewetting alter microbial communities, while beneficial microorganisms influence root water uptake, osmolytes and plant stress responses [35,36,38,39].

Eighth, irrigation research should include salinity. Repeated irrigation in poorly drained systems can increase salt accumulation, and water-saving regimes may further alter salt distribution [48].

Ninth, remote sensing should increasingly distinguish water stress from disease, nutrient deficiency and heat stress. Machine-learning and multispectral approaches provide a foundation for such multimodal classification [37].

Tenth, environmental evaluation should move beyond water savings. Energy consumption, pumping costs, greenhouse-gas implications and substrate sustainability should be incorporated into irrigation-system assessment [49].

Finally, farmer adoption and economic feasibility must become central performance indicators. A technically sophisticated irrigation controller has little

value if installation cost, connectivity requirements or operational complexity prevent practical use.

16. Conclusion

Smart irrigation scheduling represents a transition from fixed irrigation calendars toward dynamic management of crop water demand. Its fundamental advantage is not automation alone but the ability to match irrigation timing and quantity with actual soil, crop and atmospheric conditions.

Soil-moisture sensors provide information on root-zone water supply, ET-based methods quantify atmospheric demand, plant measurements reveal physiological stress, and weather forecasts provide predictive information. IoT platforms connect these data streams, while DSS, artificial intelligence and machine learning convert them into irrigation decisions [7–13,34,50].

Under water-limited conditions, this integration becomes particularly valuable because limited water must be allocated to the periods when it generates the greatest crop benefit. Moderate and strategically timed water deficits may increase water productivity, whereas severe or poorly timed stress can sharply reduce photosynthesis, reproductive development and final yield [19–23,33].

Crop response also depends on genotype, root architecture, hormonal regulation, rhizosphere biology and associated microorganisms [35,36,38,39,43,46–48]. Smart scheduling should therefore evolve toward biologically informed thresholds rather than treating crops as uniform water-demand systems.

Future systems are likely to combine continuous soil monitoring, thermal and multispectral sensing, weather forecasts, crop simulation, AI prediction and automated variable-rate irrigation. Such closed-loop irrigation will be capable of detecting emerging water stress, predicting future crop demand and applying water precisely before stress becomes yield limiting.

The broader objective should not be to maximize water saving at any cost. Instead, smart irrigation should maximize productive use of scarce water while protecting economically important crop yield and quality. Integration of agronomy, crop physiology, sensors, artificial intelligence, climate information and farmer-centred implementation offers a practical pathway toward resilient crop production under intensifying water scarcity.

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