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Research Article

More Crop Per Drop: Bridging Precision Technology and Sustainable Agriculture

Kirtika Sharma[1*], Rashmi Panwar[1], Tanushree Lohani[2], Shubhi Khare[3], Deepak Kumar[3], Tanshu Chaudhary[1]

[1]*Department of Horticulture, College of Agriculture, GBPUAT, Pantnagar*
[2]*Department of Resource Management and Consumer Science, College of Community Science, GBPUAT, Pantnagar*
[3]*Department of Soil and Water Conservation Engineering, College of Technology, GBPUAT, Pantnagar*
[*]*Email: skirtika17029@gmail.com*

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Abstract

As the global population approaches 10 billion by 2050, the agricultural sector must decouple productivity from resource exhaustion using the "More Crop Per Drop" model. This research examines the relationship between Precision Technology and Sustainable Agriculture, using the biological framework of the Soil-Plant-Atmosphere Continuum (SPAC). This strategy considers field heterogeneity as a manageable variable by including a three-layered technology architecture: Real-Time Sensing, IoT/AI-driven Analytics and Variable Rate Irrigation (VRI), resulting in Water Use Efficiency (WUE) ratings of up to 95%. Evidence-based case studies in cereal, fruit and vegetable crops show that precision interventions like Regulated Deficit Irrigation (RDI) reduce water consumption by 15-30% while improving crop quality and mitigating environmental degradation. Despite economic and technical challenges, the study concludes that precision-based sustainable intensification, through strategic government initiatives such as PMKSY 2.0 and the adoption of emerging Autonomous Systems, provides a clear path to global food security and hydrological stability in a climate-volatile future.

Keywords: Precision Irrigation, Water Use Efficiency, Evapotranspiration, IoT, VRI, SPA

Introduction

The growing global population, which is expected to reach 9.7 to 9.8 billion by 2050, poses an unprecedented challenge to the global food system, demanding a 70% increase in caloric output to ensure food security (FAO, 2017). The "water-food-climate" nexus is central to this quandary; agriculture currently accounts for more than 70% to 75% of global freshwater withdrawals, but the sector is facing increasing competition from industrial and urban demands, exacerbated by erratic hydrological patterns caused by anthropogenic climate change (UNESCO, 2021, Nikolaou *et al*., 2020, Khare et al. 2026, Kumar et al. 2025, Kumari et al. 2026). As old "more water, more yield" paradigms hit their ecological limits, the shift to a "More Crop Per Drop" attitude has transformed from a local preference to a global imperative. This strategy aims to close the gap between long-term sustainable agriculture and sophisticated precision agriculture by making sure that each unit of water is used as efficiently as possible. In the past, agricultural growth was mostly dependent on gravity-driven, conventional irrigation techniques like basin flooding and furrow flooding, which are intrinsically inefficient and can lose up to 60% of applied water to deep percolation and surface runoff (Boretti and Rosa, 2019). These inefficiencies fail to offer the adaptive capacity necessary for modern crop resistance against "flash droughts" and instead set off a chain reaction of environmental deterioration, including soil salinization and nutrient leaching (Barker *et al*., 2019, Kumar and Khare 2025, Maurya et al. 2025, Ghildiyal et al. 2025, Khare et al. 2026).

The introduction of the "Smart Farming" era provides a technical bridge to address these systemic inefficiencies by considering field variability as a controllable variable. This digital revolution is based on a sophisticated architecture of Internet of Things (IoT) sensor networks and automated control systems. Farmers can use real-time data on soil moisture and plant-based water stress indicators to adopt Variable Rate Irrigation (VRI), which has been shown to cut water consumption by 15% to 25% in cereal crops while maintaining biomass (Dahal *et al*., 2020). This level of granularity guarantees that the rhizosphere receives the appropriate amount of water, typically obtaining Water Use Efficiency (WUE) rates of up to 95%. However, the "More Crop Per Drop" mission represents a fundamental shift toward Sustainable Intensification, quantifying success through the WUE equation:

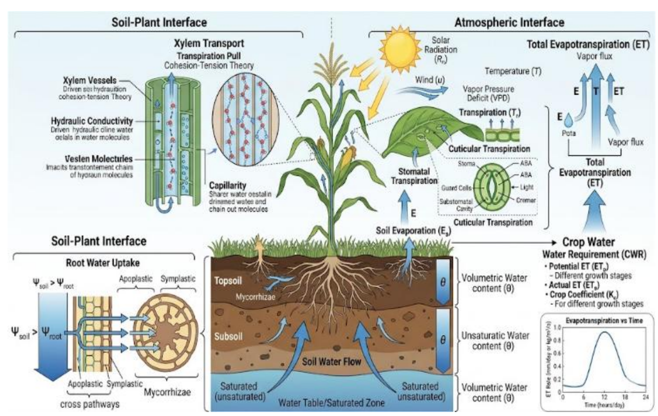
$$\text{WUE} = \frac{Crop\ Yeld}{Water\ Consumed}$$

Improving this ratio necessitates a comprehensive picture of the agricultural ecosystem, with AI models transforming datasets into usable decision-support systems (Hahn *et al*., 2022). These systems offer methods like "Deficit Irrigation," which can increase WUE by more than 30% in selected horticultural and vegetable systems (Chartzoulakis and Bertaki, 2015). Despite these obvious advantages, the shift is hampered by technical challenges and large initial capital requirements. As a result, this paper investigates the critical intersection of precision technology and sustainable practice, assessing the impact of smart tools on crop physiology and environmental health while discussing the prospects for scaling these technologies to ensure that future agricultural productivity is effectively decoupled from resource exhaustion (Ali *et al.*, 2025, Khare and Kumar 2025, Tiwari et al. 2026).

1. The Biological Foundation: The Soil-Plant-Atmosphere Continuum (SPAC)

The efficient implementation of a "More Crop Per Drop" strategy requires a fundamental understanding of the Soil-Plant-Atmosphere Continuum (SPAC), a thermodynamic framework that drives water transport along a continuous gradient of decreasing energy potential (Fig. 1). Within this continuum, water is not only taken but also transferred across a complex network of interfaces. Water intake at the Soil-Plant Interface is driven by a critical potential difference ($\Psi soil > \Psi root$). Moisture flows by apoplastic and symplastic pathways, typically assisted by mycorrhizal symbioses. Soil-Based Sensing is essential for monitoring volumetric water content (θ) and ensuring appropriate moisture availability in the rhizosphere due to biological requirements. As water enters the vascular system, Xylem Transport occurs, which is governed by the Cohesion–Tension Theory. This mechanism uses the negative pressure produced by transpiration to lift water columns through xylem vessels; monitoring this "hydraulic conductivity" via Plant-Based Sensing such as sap flow and leaf water potential enables the detection of physiological stress long before visual wilting occurs. Finally, at the Atmospheric Interface, water escapes the leaf by stomatal and cuticular transpiration, which is controlled by solar radiation and the Vapor Pressure Deficit (VPD). Precision systems can accurately calibrate irrigation to offset atmospheric demand, thereby maximizing biological efficiency (Sarkar, 2025 and Kubata, 2026), by using Atmospheric Sensing to calculate the Crop Water Requirement (CWR) balancing potential evapotranspiration (ETp) with actual evapotranspiration (ETa) via the Crop Coefficient (Kc).

Fig-1 Soil-Plant-Atmosphere Continuum (SPAC)



3. Technological Framework: The Pillars of Precision Irrigation

To meet the "More Crop Per Drop" goal, the modern agricultural system must rely on multiple interconnected technological layers that work together to bridge the gap between digital innovation and field-level sustainability. This methodology replaces traditional "guesswork" with a data-driven pipeline that optimizes resources throughout the cultivation cycle.

3.1 Sensing Layer: Real-Time Data Acquisition

The fundamental transition to precision begins with the collection of high-fidelity data from three key biological and environmental domains. Soil-based sensing uses capacitance sensors and Time Domain Reflectometry (TDR) to measure volumetric water content and soil water potential, establishing a baseline for moisture availability in the rhizosphere. Plant-based sensing, which uses sophisticated metrics like as sap flow, leaf water potential and infrared thermography to assess "Canopy Temperature Depression" (CTD), supplements this approach. CTD is a vital indicator of transpiration health and crop stress, enabling for physiological reaction before visual symptoms appear (Nikolaou *et al.,* 2020). Finally, atmospheric monitoring from on-site weather stations allows for the determination of Reference Evapotranspiration (ETo) by combining solar radiation, wind speed and vapor pressure deficit. Together, these sensors provide a multidimensional view of the agricultural ecosystem, moving away from static irrigation programs and toward a dynamic understanding of water needs.

3.2 Communication and Data Processing: The Role of IoT and AI

The Internet of Things (IoT) serves as the structural "bridge" in this structure, allowing telemetry from the sensing layer to be seamlessly transmitted to centralized cloud platforms via Low-Power Wide-Area Networks (LPWAN). In this digital world, Artificial Intelligence algorithms and machine learning models convert raw data into practical irrigation recommendations. Rather of relying on simple thresholds, these models use historical yield maps, predictive weather analytics and crop-specific growth stages measured by the Crop Coefficient (Kc) to forecast future water needs. This computational layer ensures that irrigation is a proactive technique that considers the crop's cumulative water balance (Hahn *et al*., 2022).

3.3 Actuation Layer: Variable Rate Irrigation (VRI)

The next step on the path to sustainability is the physical application of water via the Actuation Layer, notably Variable Rate Irrigation (VRI). Unlike traditional systems, which apply a constant volume across an entire field, VRI systems use Global Positioning Systems (GPS) and automated solenoid valves to provide granular control. This technology enables Sectoral Control, which adjusts flow rates for specific parts of a center pivot or lateral move system, as well as Zonal Management, which focuses on various soil types or topographic depressions within a single orchard or field. VRI prevents frequent agricultural failures such as waterlogging and nitrogen leaching in high-retention zones while ensuring enough hydration in sandy or elevated locations (Barker *et al*., 2019 and Dahal *et al*., 2020). This precision actuation is the final step in the "More Crop Per Drop" procedure, which converts digital insights into measurable water conservation and yield stability.

4. The Precision-Sustainability Bridge: Mechanisms of Action

The "More Crop Per Drop" idea is based on the transition from Reactive Irrigation (watering based on visual soil dryness) to Proactive Precision Management, which uses physiological and atmospheric demand to determine water delivery. This section describes the three key mechanisms that connect high-tech digital inputs to concrete sustainable outputs, guaranteeing that agricultural productivity is independent of resource exhaustion (Fig. 2).

4.1 Variable Rate Irrigation (VRI) and Spatial Heterogeneity

Traditional irrigation management approaches a field as a single hydrological unit, resulting in "over-irrigation" in low-lying, clay-rich sections and "under-irrigation" in sandy, higher zones. The use of Variable Rate Irrigation (VRI) in conjunction with Global Positioning Systems (GPS) and Geographic Information Systems (GIS) enables water prescription at the individual nozzle level. VRI systems use electromagnetic induction (EMI) to map soil texture and topography and then alter flow rates in real time to meet the unique water-holding capacity of each field zone. This tailored approach prevents anaerobic conditions in saturated zones, lowering nitrous oxide (N_2O) emissions and reduces deep percolation in sandy zones, protecting groundwater from nitrate leaching (Barker *et al*., 2019 and Dahal *et al*., 2020).

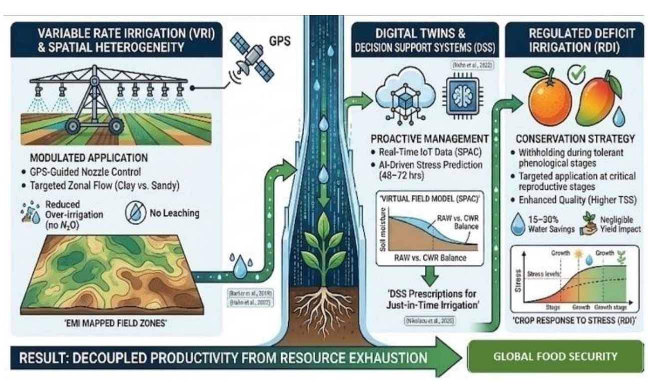
4.2 Digital Twins and Decision Support Systems (DSS)

An important computational bridge in modern sustainable agriculture is the "Digital Twin," which is a virtual representation of the actual field fed by constant streams of IoT data. These Decision Support Systems (DSS) use the Crop Coefficient (Kc) and real-time Evapotranspiration (ETc) data to estimate the plant's daily water balance. The DSS's artificial intelligence (AI) and machine learning algorithms can detect moisture stress 48-72 hours before it is obvious to the human eye. This enables "Just-in-Time" watering, which ensures that the crop never hits the Permanent Wilting Point (PW). By keeping soil moisture within the "Readily Available Water" (RAW) range, these methods maximize harvest index while reducing total amount of water withdrawn from aquifers (Hahn *et al*., 2022).

4.3 Regulated Deficit Irrigation (RDI) as a Conservation Strategy

Precision technology allows for the skilled administration of Regulated Deficit Irrigation (RDI), a sustainable method in which water is intentionally withheld during drought-tolerant phenological periods and fully applied during important reproductive stages. In horticultural crops such as mango and Malta, RDI is used to regulate vegetative growth and improve fruit quality indicators like Total Soluble Solids (TSS). However, RDI is high-risk and necessitates high-fidelity monitoring with sap flow sensors and infrared thermography to avoid lasting xylem damage. When combined with precision tools, RDI can cut overall water use by 15-30% while having no effect on final output, significantly boosting the Water Use Efficiency (WUE) ratio and guaranteeing long-term hydrological stability (Nikolaou *et al*., 2020 and Chartzoulakis and Bertaki, 2015).

Fig. 2: The Precision-Sustainability Bridge: Mechanisms of Action



5. Environmental and Economic Synergies

The implementation of precision technology into sustainable agriculture generates a "Double Dividend," boosting both ecological health and economic viability. This section investigates how high-efficiency water management contributes to overall sustainability and financial resilience.

5.1 The Energy-Water Nexus and Carbon Mitigation

Water management and energy usage are deeply interconnected, forming the Energy-Water Nexus. Traditional irrigation necessitates a significant amount of electrical or diesel power to pump and distribute huge, homogeneous amounts of water. Precision scheduling can reduce total water application by 20-30%, which reduces the energy demand for extraction (Nikolaou *et al*., 2020). Furthermore, precise systems reduce climate change by limiting soil saturation. Waterlogged soils are the principal source of methane (CH_4) and nitrogen dioxide (N_2O) emissions. Precision irrigation reduces greenhouse gas emissions and the carbon footprint per kilogram of produce by sustaining aerobic soil conditions via sensor-based delivery (Boretti and Rosa, 2019, Khare et al. 2025, 2026).

5.2 Nutrient Use Efficiency (NUE) and Precision Fertigation

Smart Fertigation uses precision technologies to bridge the gap between hydrological control and crop nutrition. This technique distributes dissolved nutrients to the active rhizosphere with pinpoint accuracy. Targeted application reduces "nutrient leaching," in which surplus water transports nitrates into subsurface aquifers, resulting in eutrophication. According to empirical research, precision fertigation can boost Nutrient Use Efficiency (NUE) by up to 40% (Debnath *et al*., 2022). This guarantees that nutrients are digested by the plant rather than lost to the environment, decreasing the farmer's reliance on costly inputs and preserving the health of nearby watersheds.

5.3 Economic Resilience and Market Competitiveness

Beyond resource savings, the "More Crop Per Drop" method improves economic resilience to climatic unpredictability. Farmers can sustain steady yields during periods of limited water availability by boosting their Water Use Efficiency (WUE) ratio. Furthermore, increased quality metrics related with precision management, such as higher Total Soluble Solids (TSS) in fruits like Mango and Malta, enable farmers to command better export prices. The expensive initial capital investment in precision infrastructure is mitigated by long-term cost savings and enhanced market value for sustainably cultivated produce (Hahn *et al*., 2022 and Chartzoulakis and Bertaki, 2015).

6. Precision Interventions Across Crop Systems

6.1 Agronomic and Cereal Crops: Spatial Optimization in Broad-Acre Farming

In large-scale agronomy, particularly for maize (*Zea mays*), the primary challenge to the "More Crop Per Drop" philosophy is soil texture's inherent spatial heterogeneity. Traditional uniform irrigation frequently causes both overwatering and moisture stress within the same field. Barker *et al*. (2019) found that combining Variable Rate Irrigation (VRI) with remote-sensing-based evapotranspiration models can greatly improve resource use. While VRI did not reduce grain yields, it did result in lower mean prescribed gross irrigation depths than uniform treatments, especially under deficit irrigation situations (Barker *et al*., 2019). Furthermore, Dahal *et al*. (2020) found that integrating variable rate water and nitrogen management can improve Water Use Efficiency (WUE) and reduce nitrate leaching, demonstrating the need of precision technology in achieving sustainable agriculture intensification.

6.2. Perennial Fruit Science: Productivity and Quality in High-Density Orchards

Fruit science presents a unique potential for precision technology due of the crops' high value and susceptibility to water stress. In Mango (*Mangifera indica*), research into Regulated Deficit Irrigation (RDI) managed through IoT-based soil moisture sensors has shown that applying 50-75% of the full Crop

Evapotranspiration (ETc) during specific vegetative stages can maintain yields while improving water productivity by nearly 60% (Hahn *et al*., 2022). Precision management of grapes (*Vitis vinifera*) through "Partial Root-zone Drying" (PRD) and sap flow monitoring allows for a 20-30% reduction in water application, which triggers a beneficial stress response that increases the concentration of anthocyanins and sugars, directly boosting market value. Similarly, Mali *et al*. (2015) discovered that drip irrigation at 60% ETc beginning with the blossoming stage resulted in the maximum litchi fruit weight and sugar content. While the best water use efficiency was achieved at 20% ETc, conventional basin irrigation resulted in a 10.2% fruit cracking rate due to moisture stress, demonstrating that precision drip-based deficit irrigation maintains quality with minimum yield deviation. According to Kadbhane (2025), drip irrigation with three emitters (DI3) outperformed traditional free flooding in pomegranates, increasing yields by 55% and fruit weight by 65%. Over the course of a three-year research, this precision approach increased water productivity by 64% and had the highest benefit-to-cost ratio. Using CROPWAT-8.0 and soil sensors to calibrate supply, the DI3 system emerged as the most efficient model for increasing both pomegranate production and financial returns. By combining IoT sensors and precision nutrient management, these HDP systems produce a production ratio nearly three times that of typical orchards, ensuring that high-value fruit science stays resilient in the face of acute drought.

6.3. Vegetable Crops: Closed-Loop Precision in Protected Cultivation

Vegetable crops including tomatoes, okra and capsicum are extremely susceptible to irregular hydrological patterns, making precision water delivery critical for productivity and fruit quality. Yang *et al*. (2018) found that Regulated Deficit Irrigation (RDI) in Northwest China reduced chili pepper evapotranspiration by 2-27% while increasing fruit quality with higher total soluble solids. While full irrigation produced the maximum yields, creating a 25-50% water deficit during the late development stage resulted in the highest water productivity and economic advantage. Conversely, deficits during the middle stage resulted in the greatest yield losses (13-20%), highlighting the importance of growth-stage-specific precision management. Suvitha *et al*. (2021) observed that tensiometer-based drip irrigation in Tamil Nadu increased tomato yield to 96.21 t/ha while maximizing water use efficiency (25.42 t ha-mm^{-1}). This precision approach saved up to 60.55% more water than traditional methods, closely followed by soil moisture sensor-based irrigation. These findings demonstrate the efficiency of automated sensing in improving resource allocation in vegetable cultivation. Singh *et al*. (2023) created an IoT-based autonomous framework for tomato growing that uses sensor modules to predict soil moisture and automate irrigation schedules. Large-scale validation demonstrates that this method increases yields significantly by optimizing resource use and giving real-time crop health data via a smartphone application. Londhe (2025) demonstrated that summer okra growing in Maharashtra is most economically viable with drip irrigation at 100% ETc and silver-black plastic mulch, yielding a maximum of 17.54 q ha^{-1}. The treatment with the best growth parameters and a peak benefit-cost ratio of 1.79 resulted in the highest water use efficiency (36.83 kg $ha^{-1}cm^{-1}$) at a lowered irrigation level of 60% ETc with mulching. These findings highlight the importance of combining plastic mulch with precise scheduling for maximizing production and conserving resources in semi-arid situations. This demonstrates that for vegetable crops, the precision "bridge" enables a near-zero-waste strategy that balances high production and resource conservation.

7. Implementation Barriers and Solutions

Despite the scientifically demonstrated benefits of the "More Crop Per Drop" strategy, the move from traditional to precision-based sustainable agriculture is fraught with socioeconomic and technical challenges. This section outlines the key challenges to adoption and proposes strategic strategies to close the gaps.

7.1 Economic Constraints: High Initial Capital and Return on Investment (ROI) The biggest obstacle to widespread adoption is the expensive "entry cost" of precision infrastructure, such as IoT networks and VRI systems, which frequently surpasses the liquidity of small-to-medium-sized farms. To address this issue, governments and banks must shift from traditional input subsidies to technology-based incentives, such as low-interest "green loans" and carbon-credit programs. These financial mechanisms incentivize water-saving methods and significantly accelerate the Return on Investment (ROI), making high-tech stewardship economically feasible.

7.2 Technical Complexity and the "Digital Divide" As farmers move from intuition-based practices to data-driven management, they frequently experience "technology fatigue" when confronted with sophisticated AI prescriptions and satellite datasets. This difficulty needs the creation of User-Centric Decision Support Systems (DSS) that offer simplified, mobile-friendly "irrigation triggers" rather than overwhelming raw data. Furthermore, enhancing agricultural extension services is crucial for providing the human-expert support required to successfully manage the "Big Data" transformation.

7.3 Infrastructure and Data Connectivity Infrastructure and Data Connectivity Precision agriculture is strongly reliant on effective rural connectivity (4G/5G/LoRaWAN), however many remote or mountainous places, such as Uttarakhand's high-altitude belts, experience inconsistent internet availability, disrupting real-time data transmission. Beyond prioritizing regional digital infrastructure, a crucial answer is the development of "Edge Computing," which processes data locally at the sensor level rather than in the cloud. This permits precision systems to function and operate autonomously even in places with inadequate or unstable connectivity.

8. Government Initiatives for Precision Irrigation

To support with the shift to "More Crop Per Drop," targeted governmental programs have been created to reduce barriers to precision technology adoption. These projects prioritize financial incentives, digital infrastructure and automation to assure long-term water and food security.

8.1 Financial Subsidies and Modernization: Governments are focusing on modernizing irrigation infrastructure to close the gap between traditional and precision systems. Under the PMKSY 2.0 framework, small and marginal farmers receive up to 55% subsidy for micro-irrigation gear. The Micro Irrigation Fund (MIF) offers a ₹10,000 Cr corpus for top-up subsidies, which can reach 80-90% in selected states (**MoA&FW**, 2025 and NABARD, 2025). Crucially, initiatives like the M-CADWM are replacing inefficient open canals with pressurized pipe networks, allowing for "plug-and-play" drip irrigation at the field level (Bhadur, 2025).

8.2 Digital Public Infrastructure (DPI): The establishment of a solid foundation Digital Public Infrastructure (DPI) is critical for scaling sustainable practices. Bharat-VISTAAR uses multilingual AI to deliver real-time, voice-based irrigation advisories, while the AgriStack program uses digital farmer IDs and land data to establish accurate water and fertilizer requirements (NITI Aayog, 2025 and **MoA&FW**, 2026). Furthermore, Krishi-DSS provides a satellite-based decision support system that monitors crop water stress and automates irrigation, thus providing farmers with a digital twin of their fields to maximize water consumption (ISRO, 2025).

8.3 Smart Tech and Automation: To promote "Smart Farming," initiatives are focusing on high-tech solutions and capacity training. IoT and AI pilots are implementing smart valves and soil sensors to prevent over-irrigation in various climate zones. The government funds Drone Technology outfitted with thermal sensors for high-resolution moisture sensing via the Sub-Mission on Agricultural Mechanization (**MoA&FW**, 2025). Local Precision Farming Centres complement these efforts by providing hands-on instruction and personalized irrigation plans, making modern technology tools more accessible and practical for the typical farm (ICAR, 2025).

9. Future Prospects and Conclusion

The shift to fully autonomous irrigation systems, as well as the democratization of AgTech, will enable smallholder farmers to access high-level decision support via low-cost, "plug-and-play" IoT sensors and open-source AI models. Emerging innovations like as nano-sensors for real-time nutrient tracking and swarm robotics for targeted micro-irrigation offer the next frontier in reducing farming's environmental footprint. Furthermore, as the worldwide Carbon Credit Market matures, farmers that use precise equipment will most likely be financially reimbursed for their contributions to groundwater preservation and carbon sequestration, transforming sustainable water management into a supplementary revenue stream. Finally, linking precise technology and sustainable agriculture is no longer a local preference, but rather a worldwide obligation; as demonstrated throughout this article, the synergy between digital innovation and agroecology provides a clear path to long-term food security. While implementation constraints such as costly initial capital and the "digital divide" remain, they are being gradually removed by strong government programs such as PMKSY 2.0 and the Digital Agriculture Mission. As climate change continues to disrupt global hydrological cycles, the ability to decouple agricultural productivity from resource exhaustion using the "More Crop Per Drop" approach will be the defining metric of success for 21st-century agriculture, ensuring hydrological, economic and ecological stability for a population approaching 10 billion.

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