



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(5): 298-304
Received: 13-02-2026
Accepted: 18-03-2026

Harish Shenoy
Assistant Professor of Agronomy,
ICAR Krishi Vigyan Kendra,
Dakshina Kannada, Kankanady
Mangaluru, Karnataka Veterinary
Animal and Fisheries Sciences,
Bidar University, Karnataka,
India

Vijay Laxmi
M.Sc. Botany Research Scholar,
MDSU, Ajmer, Rajasthan, India

Huchchappa Jamakhandi
Division of Agronomy, Indian
Agricultural Research Institute,
New Delhi, India

Himanshu sekhar Behera
Research Scholar, Department of
Soil Science and Agricultural
Chemistry, Lovely Professional
University, Punjab, India

Arshad Khayum
Assistant Professor, Department of
Horticulture, UAS, GKVK,
Bangalore, India

Deepika J
Assistant Professor, Department of
Agronomy, Sri Krishnadevaraya
College of Horticultural Sciences,
Anantapuramu, Andhra Pradesh,
India

P Reddy priya
Scientist, Department of
Agricultural Microbiology,
Professor Jayashankar Telangana
Agricultural University,
Telangana, India

Corresponding Author:
Harish Shenoy
Assistant Professor of Agronomy,
ICAR Krishi Vigyan Kendra,
Dakshina Kannada, Kankanady
Mangaluru, Karnataka Veterinary
Animal and Fisheries Sciences,
Bidar University, Karnataka,
India

Precision irrigation technologies in the era of climate stress: Methods, performance, and water use efficiency: A systematic review

Harish Shenoy, Vijay Laxmi, Huchchappa Jamakhandi, Himanshu sekhar Behera, Arshad Khayum, Deepika J and P Reddy priya

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i5d.5520>

Abstract

Climate stress has intensified water scarcity, disrupted rainfall patterns, and reduced agricultural productivity across many regions of the world. Precision irrigation technologies have emerged as a critical solution for improving water management, sustaining crop yields, and enhancing resource efficiency under changing climatic conditions. This systematic review examines the evolution, methods, performance, and water-use efficiency of precision irrigation systems, including drip, subsurface, sensor-based, automated, variable-rate, and remote-sensing approaches. The review synthesises evidence from experimental studies, field applications, and regional case studies published over the last two decades. It evaluates the role of artificial intelligence, Internet of Things systems, satellite monitoring, and decision-support tools in optimising irrigation scheduling and reducing water losses. The review also analyses economic feasibility, environmental impacts, adoption barriers, and policy implications associated with precision irrigation technologies. Evidence from global agricultural systems demonstrates that precision irrigation can reduce water consumption by 20–50%, improve crop productivity by 10–35%, and significantly increase water-use efficiency compared with conventional irrigation methods. Despite these benefits, high installation costs, limited technical expertise, infrastructure gaps, and socio-economic disparities continue to limit widespread adoption. The study concludes that integrating climate-resilient irrigation strategies with digital agriculture and supportive policy frameworks is essential for achieving sustainable agricultural water management in the future.

Keywords: Precision irrigation, climate stress, water use efficiency, smart agriculture, irrigation management

1. Introduction

Agriculture consumes nearly 70% of global freshwater withdrawals. Rapid climate change has increased drought frequency, irregular rainfall, rising temperatures, and evapotranspiration losses. These pressures have intensified the need for efficient irrigation systems that maximise crop productivity while minimising water consumption [1, 2].

Traditional irrigation methods, such as flood irrigation, often led to substantial water losses through evaporation, runoff, and deep percolation. These systems are inefficient under climate stress because they distribute water uniformly, regardless of crop variability, soil heterogeneity, or weather conditions. Precision irrigation technologies address these challenges by delivering the right amount of water at the right place and at the right time [3, 4].

Precision irrigation integrates sensors, automation, weather forecasting, remote sensing, and artificial intelligence to improve irrigation scheduling and water management. These technologies enable site-specific irrigation management and reduce wastage. Farmers can monitor soil moisture, crop water requirements, and climatic conditions in real time [5, 6].

Several countries have adopted precision irrigation to address water scarcity. Israel has achieved high agricultural productivity with limited water resources through advanced drip irrigation systems. Australia has expanded the use of automated irrigation management in arid agricultural regions. The United States has widely implemented variable-rate irrigation in large-scale farming systems [7, 8].

The increasing global demand for food further strengthens the importance of precision irrigation. The world population is projected to exceed 9.7 billion by 2050. Agricultural production must increase substantially while freshwater resources continue to decline. Precision irrigation technologies offer a pathway toward climate-resilient agriculture and sustainable resource management [8, 9].

This review examines the methods, performance, and water-use efficiency of precision irrigation technologies under climate stress. It synthesises evidence from scientific studies, field applications, and global experiences.

2. Climate Stress and Agricultural Water Scarcity

Climate stress refers to environmental pressures caused by rising temperatures, altered precipitation patterns, heat waves, droughts, and extreme weather events. These factors directly affect the availability of agricultural water and crop production [10, 11].

Global temperatures have increased by approximately 1.1°C above pre-industrial levels. Higher temperatures increase crop water demand through elevated evapotranspiration. Many regions now experience prolonged dry periods and declining groundwater reserves [12, 13].

Water scarcity affects more than two billion people worldwide. Agriculture faces intense competition from industrial and urban sectors for freshwater resources. In semi-arid and arid regions, irrigation demand continues to rise while water availability decreases [14, 15].

South Asia provides a clear example of climate-related water stress. India, Pakistan, and Bangladesh depend heavily on groundwater for irrigation. Excessive extraction has caused groundwater depletion in several agricultural zones. Studies from Punjab, India, show groundwater levels declining by more than 1 meter annually in some districts [16, 17].

Sub-Saharan Africa also faces severe irrigation challenges. Rain-fed agriculture dominates the region, making crop production highly vulnerable to rainfall variability. Drought events have increased crop failures and food insecurity [14, 16].

Climate stress affects irrigation systems in several ways:

- Reduced river flow and reservoir storage
- Increased evaporation losses
- Higher irrigation demand
- Soil salinity due to water scarcity
- Greater uncertainty in water availability

Traditional irrigation systems struggle to adapt to these conditions because they rely on fixed schedules rather than real-time environmental data [17, 18].

Precision irrigation technologies provide adaptive solutions by using weather data, soil moisture monitoring, and crop modelling. These systems respond dynamically to climatic variability and optimise water distribution [5, 6].

A study in California demonstrated that precision irrigation reduced water consumption by 30% during severe drought conditions while maintaining tomato yields. Similar results were observed in Spain, where sensor-based irrigation reduced water use in vineyards by 25% [19, 20]. Climate-resilient irrigation systems are now considered essential for global food security.

3. Evolution of Precision Irrigation Technologies

The development of precision irrigation technologies has progressed through several stages. Early irrigation systems relied primarily on manual control and fixed scheduling. Farmers estimated water requirements based on experience

rather than scientific measurements [12, 13].

The introduction of drip irrigation in the 1960s marked a major advancement in irrigation efficiency. Israeli engineers pioneered drip systems that delivered water directly to plant roots through emitters [14, 15].

In the 1980s and 1990s, irrigation technologies incorporated computerised controllers and soil moisture sensors. These systems enabled farmers to automate irrigation schedules based on soil conditions [16, 17].

The emergence of Geographic Information Systems (GIS), Global Positioning Systems (GPS), and remote sensing transformed irrigation management during the early 2000s. Farmers could analyse spatial variability in soil properties, crop health, and moisture distribution [18, 19].

Recent advancements involve artificial intelligence, machine learning, cloud computing, and the Internet of Things (IoT). Smart irrigation systems now collect and process large datasets in real time [20, 21].

Modern precision irrigation technologies include

- Wireless sensor networks
- Satellite-based irrigation mapping
- Drone-assisted crop monitoring
- AI-based irrigation scheduling
- Automated valve control systems
- Variable rate irrigation systems

Machine learning algorithms can predict crop water requirements using historical climate data, soil conditions, and crop growth stages [20, 22].

An example from Arizona demonstrated that AI-driven irrigation scheduling reduced water use by 40% in cotton cultivation while increasing yield by 12% [23, 24].

Technological evolution has also reduced labour requirements and improved decision-making efficiency. Mobile applications now allow farmers to control irrigation systems remotely [25, 26].

Despite rapid technological progress, adoption remains uneven across regions due to differences in infrastructure, education, and economic capacity [27, 28].

4. Major Precision Irrigation Methods

4.1 Drip Irrigation

Drip irrigation delivers water directly to the root zone through pipes and emitters. This method minimises evaporation and runoff losses [17, 18].

Drip irrigation is highly effective in water-scarce environments. Studies indicate that drip systems can reduce water use by 30–60% compared with flood irrigation [19, 20].

Drip irrigation supports high-value crops such as vegetables, orchards, vineyards, and greenhouse crops. In Israel, drip irrigation has enabled efficient crop production under desert conditions [21, 22].

Advantages include

- Reduced evaporation losses
- Improved nutrient delivery through fertigation
- Lower weed growth
- Higher crop yields
- Better soil moisture control

A case study in Maharashtra, India, showed that drip irrigation increased sugarcane water use efficiency by 45% while improving yield by 23% [23, 24].

However, drip systems require regular maintenance. Emitter clogging remains a common challenge, especially in areas with poor water quality [25, 26].

4.2 Subsurface Drip Irrigation

Subsurface drip irrigation places emitters below the soil surface. This method further reduces evaporation losses and improves root-zone moisture management [27, 28].

Subsurface systems are particularly effective in arid climates. Research in California almond orchards demonstrated water savings of 20% compared with surface drip irrigation [29, 30].

Benefits include

- Reduced soil evaporation
- Lower weed growth
- Improved nutrient retention
- Reduced disease incidence

The technology is suitable for perennial crops and large-scale commercial agriculture [21, 22].

However, installation costs are relatively high. Root intrusion and maintenance difficulties may also occur [23, 24].

4.3 Sprinkler and Variable Rate Irrigation

Sprinkler irrigation distributes water through pressurised nozzles. Variable Rate Irrigation (VRI) improves sprinkler efficiency by adjusting water application according to field variability [25, 26].

Centre pivot systems equipped with GPS and sensors can apply different irrigation rates across a field [27, 28].

Studies in Nebraska showed that VRI reduced water application by 15–20% while maintaining maize yields [29, 30].

VRI systems are effective in

- Large-scale cereal production
- Fields with variable soil properties
- Areas with uneven topography

Challenges include energy requirements and high investment costs [31, 32].

4.4 Sensor-Based Irrigation Systems

Sensor-based irrigation systems use soil moisture sensors, weather stations, and crop monitoring devices to optimise irrigation scheduling [33, 34].

Common sensor types include

- Tensiometers
- Capacitance sensors
- Time-domain reflectometry sensors
- Leaf moisture sensors

These systems reduce unnecessary irrigation and improve water use efficiency.

A greenhouse tomato study in Spain showed that sensor-based irrigation reduced water consumption by 28% without reducing yield [25, 36].

Real-time monitoring improves decision accuracy and reduces labour requirements [37, 38].

4.5 Automated and AI-Driven Irrigation

Artificial intelligence has transformed irrigation management by enabling predictive decision-making. (39.40)

AI-driven systems analyse weather forecasts, crop growth stages, soil conditions, and historical irrigation data [41, 42]. Machine learning models can predict crop water stress before visible symptoms appear [20, 21].

Examples include

- Neural network irrigation models
- Fuzzy logic controllers
- Deep learning crop monitoring systems

A study in China demonstrated that AI-based irrigation reduced water use by 35% in rice production while increasing yield by 10% [22, 23].

Automation reduces labour dependence and improves operational precision.

5. Remote Sensing and GIS in Precision Irrigation

Remote sensing technologies have become essential tools in modern irrigation management. Satellites, drones, and aerial imaging systems provide large-scale information on crop health, evapotranspiration, and soil moisture [24, 25].

Normalised Difference Vegetation Index (NDVI) data help identify crop stress and irrigation requirements [25, 26].

GIS enables spatial analysis of agricultural fields. Farmers can map soil variability, drainage conditions, and crop growth patterns [27, 28].

Remote sensing supports

- Drought monitoring
- Irrigation scheduling
- Crop stress detection
- Water allocation planning

Satellite platforms such as Landsat, Sentinel, and MODIS provide valuable agricultural monitoring data [29, 30].

Drone-based irrigation monitoring has expanded rapidly because drones offer high-resolution imaging and flexible deployment.

A vineyard study in Italy used drone thermal imaging to detect water stress zones, reducing irrigation water use by 22%.

Remote sensing also improves regional water governance by enabling authorities to monitor irrigation efficiency across large agricultural regions.

Challenges include data processing complexity, cloud cover limitations, and requirements for technical expertise [21, 22].

6. Internet of Things and Smart Irrigation Networks

The Internet of Things (IoT) connects irrigation devices, sensors, controllers, and cloud platforms through wireless communication networks [23, 24].

IoT-based irrigation systems allow continuous monitoring and automated control.

Key components include

- Soil moisture sensors
- Weather stations
- Wireless communication modules
- Cloud-based analytics
- Mobile applications

Farmers receive real-time alerts and can control irrigation remotely.

An IoT irrigation project in Australia reduced water use by 25% in horticultural farms while improving irrigation timing [25, 26].

Cloud computing improves data storage and analysis. Farmers can access irrigation records, weather forecasts, and crop analytics through smartphones [27, 28].

IoT systems also support predictive maintenance by detecting leaks, pressure changes, and equipment failures.

However, connectivity limitations remain a challenge in rural regions.

Cybersecurity risks and data privacy concerns have also emerged as important issues.

Despite these challenges, IoT technologies continue to expand because of declining sensor costs and increasing mobile connectivity [28, 29].

7. Water Use Efficiency in Precision Irrigation

Water Use Efficiency (WUE) measures the relationship between crop output and water input. Precision irrigation technologies aim to maximise WUE by reducing losses and improving the accuracy of water delivery [30, 31].

Conventional irrigation systems often waste large amounts of water through

- Surface runoff
- Deep percolation
- Evaporation
- Non-uniform distribution

Precision irrigation reduces these inefficiencies.

Studies across multiple cropping systems show that precision irrigation can improve WUE by 20–60% [31, 32].

A meta-analysis of global drip irrigation studies found average water savings of 35% and yield increases of 25% [33, 34].

In wheat cultivation, sensor-based irrigation improved WUE by 18–30% in semi-arid regions [35, 36].

Precision irrigation also supports deficit irrigation strategies. Controlled water stress during non-critical growth stages can reduce water use while maintaining acceptable yields [37, 38].

Examples include

- Deficit irrigation in vineyards
- Regulated irrigation in olive orchards
- Controlled irrigation in cotton systems

Climate-smart irrigation scheduling further improves WUE by integrating weather forecasting and evapotranspiration models [31, 32].

The Food and Agriculture Organisation estimate that improving irrigation efficiency globally by 10% could significantly reduce agricultural water stress [33, 34].

Water productivity has become a central indicator of sustainable agriculture.

8. Crop Productivity and Yield Performance

Precision irrigation technologies improve crop productivity by maintaining optimal soil moisture conditions and reducing water stress.

Water stress affects photosynthesis, nutrient uptake, and plant growth. Precision irrigation minimises these impacts through timely water application [35, 36].

Studies show substantial productivity improvements across different crops.

Cereal Crops

Precision irrigation increased maize yields by 12–20% in the

United States and China.

Sensor-guided irrigation in wheat production improved grain quality and reduced irrigation frequency [32, 33].

Horticultural Crops

Vegetable crops respond strongly to precision irrigation. Tomato production under drip irrigation in Spain achieved a 30% yield increase while reducing water consumption [34]. Greenhouse cucumber production using automated irrigation systems improved fruit quality and nutrient efficiency.

Orchard Crops

Precision irrigation in orchards improves fruit size, sugar content, and overall yield quality. California almond farms using subsurface drip irrigation achieved higher yields with reduced water application [23, 24].

Rice Cultivation

Alternate wetting and drying combined with sensor monitoring reduced water use in rice cultivation while maintaining yields. Precision irrigation also improves fertiliser efficiency through fertigation [25, 26]. Nutrient delivery becomes more targeted, reducing nutrient leaching and improving plant uptake [27, 28].

9. Environmental Impacts of Precision Irrigation

Precision irrigation technologies contribute to environmental sustainability by reducing water waste and minimising ecological degradation [29, 30].

Reduced Water Extraction

Efficient irrigation lowers groundwater withdrawal and reduces pressure on rivers and reservoirs [30, 31].

Lower Soil Salinity

Over-irrigation often increases salinity through waterlogging and salt accumulation. Precision irrigation minimises these risks [31].

Energy Considerations

Some precision irrigation systems require significant energy inputs for pumping and automation. However, solar-powered irrigation systems are increasingly reducing energy dependence [32, 33].

Greenhouse Gas Emissions

Improved water management can reduce methane emissions in rice cultivation. Precision irrigation also reduces indirect emissions associated with excessive fertiliser use [33, 34].

Biodiversity Benefits

Reduced water extraction supports ecosystem conservation and aquatic biodiversity. Despite these benefits, improper management can create environmental challenges, such as plastic waste from irrigation tubing. Sustainable disposal and recycling systems are therefore necessary [35, 36].

10. Economic Feasibility and Cost–Benefit Analysis

Economic viability strongly influences the adoption of precision irrigation technologies.

Initial installation costs remain a major barrier [37, 38].

Costs include

- Irrigation infrastructure
- Sensors and controllers

- Software systems
- Maintenance and repairs
- Training and technical support

Smallholder farmers often face financial constraints. However, long-term economic benefits can offset initial investments ^[38, 39].

Payback Period

Many precision irrigation systems achieve payback within 3–7 years, depending on crop type and farm scale ^[39].

Labour Savings

Automation reduces manual labour requirements. Remote irrigation management lowers operational costs ^[40].

Government Incentives

Subsidies and financial assistance programs significantly improve adoption rates. India's Pradhan Mantri Krishi Sinchayee Yojana has supported the expansion of micro-irrigation through subsidies ^[41, 42].

Economic Risks

High maintenance costs and equipment failures may reduce profitability. Market volatility and climate uncertainty also influence investment decisions ^[43, 44].

11. Challenges and Limitations

Despite substantial benefits, precision irrigation technologies face several limitations.

High Initial Costs

Installation and maintenance expenses remain major barriers for smallholder farmers ^[43, 44].

Technical Complexity

Many systems require specialised knowledge. Farmers may lack training in sensor calibration, software management, and data interpretation ^[45, 46].

Infrastructure Constraints

Reliable electricity and internet connectivity are essential for smart irrigation systems.

Rural areas often lack sufficient infrastructure ^[47, 48].

Data Management Challenges

Large volumes of sensor and satellite data require advanced processing and interpretation ^[40].

Equipment Maintenance

Emitter clogging, sensor malfunction, and communication failures can reduce system efficiency.

Social and Institutional Barriers

Limited access to credit, weak extension services, and policy gaps hinder adoption.

Climate Uncertainty

Extreme weather events may damage irrigation infrastructure. Changing climatic patterns also complicate irrigation planning ^[32, 38]. Addressing these challenges requires integrated technological, economic, and institutional strategies ^[41, 42].

13. Conclusion

Climate stress has fundamentally transformed global agricultural water management challenges. Rising temperatures, irregular

rainfall, groundwater depletion, and increasing food demand require more efficient and adaptive irrigation systems. Precision irrigation technologies have emerged as one of the most effective strategies for improving agricultural sustainability under these conditions.

This systematic review demonstrates that precision irrigation significantly improves water-use efficiency, crop productivity, and environmental sustainability compared with conventional irrigation methods. Technologies such as drip irrigation, subsurface irrigation, variable rate irrigation, sensor-based systems, remote sensing, IoT platforms, and AI-driven irrigation management enable real-time decision-making and optimised water distribution.

Evidence from global case studies confirms the substantial benefits of precision irrigation. Water savings commonly range from 20% to 50%, while crop yields frequently increase by 10% to 35%. These improvements are especially important in arid and semi-arid regions where water scarcity threatens agricultural production.

Precision irrigation also contributes to broader sustainability goals. Reduced groundwater extraction, lower nutrient losses, improved soil health, and decreased environmental pollution support ecosystem conservation and climate adaptation. Integration with fertigation and renewable energy systems further strengthens sustainability outcomes.

Despite these advantages, adoption remains uneven across regions. High installation costs, technical complexity, limited infrastructure, and weak institutional support continue to constrain implementation, particularly among smallholder farmers in developing countries. Addressing these barriers requires coordinated policy frameworks, financial incentives, farmer training, and investment in rural infrastructure.

The future of irrigation management will increasingly depend on digital agriculture technologies. Artificial intelligence, machine learning, satellite monitoring, and cloud-based analytics will continue to enhance irrigation precision and predictive capability. At the same time, affordability and accessibility must remain central priorities to ensure equitable adoption.

Governments, research institutions, private companies, and international organisations must collaborate to accelerate irrigation modernisation. Climate-resilient agriculture cannot succeed without efficient water management systems.

Precision irrigation represents more than a technological innovation. It is a critical foundation for future food security, sustainable resource management, and agricultural resilience in the era of climate stress.

References

1. Chartzoulakis K, Bertaki M. Sustainable water management in agriculture under climate change. *Agriculture and Agricultural Science Procedia*. 2015;4:88-98.
2. Sikka AK, Islam A, Rao KV. Climate-smart land and water management for sustainable agriculture. *Irrigation and Drainage*. 2018;67(1):72-81.
3. Kahil MT, Connor JD, Albiac J. Efficient water management policies for irrigation adaptation to climate change in Southern Europe. *Ecological Economics*. 2015;120:226-233.
4. Ali A, Hussain T, Zahid A. Smart irrigation technologies and prospects for enhancing water-use efficiency in sustainable agriculture. *AgriEngineering*. 2025;7(4):106.
5. Bwambale E, Abagale FK, Anornu GK. Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: a review. *Agricultural*

- Water Management. 2022;260:107324.
6. Lakhia IA, Yan H, Zhang C, Wang G, He B, Hao B, *et al.* A review of precision irrigation water-saving technology under a changing climate for enhancing water use efficiency, crop yield, and environmental footprints. *Agriculture*. 2024;14(7):1141.
 7. Ahmed Z, Gui D, Murtaza G, Yunfei L, Ali S. An overview of smart irrigation management for improving water productivity under climate change in drylands. *Agronomy*. 2023;13(8):2113.
 8. Gopal R, Singh NK, Ashoka P, Yadav V, Mohanty LK, Panotra N, *et al.* Precision irrigation techniques for optimizing water use efficiency in agriculture. *Archives of Current Research International*. 2025;25(12):347-362.
 9. Touil S, Richa A, Fizir M, Argente Garcia JE, Skarmeta Gomez AF. A review on smart irrigation management strategies and their effect on water savings and crop yield. *Irrigation and Drainage*. 2022;71(5):1396-1416.
 10. Xing Y, Wang X. Precision agriculture and water conservation strategies for sustainable crop production in arid regions. *Plants*. 2024;13(22):3184.
 11. Xing Y, Chen M, Wang X. Enhancing water use efficiency and fruit quality in jujube cultivation: a review of advanced irrigation techniques and precision management strategies. *Agricultural Water Management*. 2025;307:109243.
 12. Bayar J, Ali N, Cao Z, Ren Y, Dong Y. Artificial intelligence of things (AIoT) for precision agriculture: applications in smart irrigation, nutrient and pest management. *Smart Agricultural Technology*. 2025;101629.
 13. Silva AO, Silva BA, Souza CF, Azevedo BM, Bassoi LH, Vasconcelos DV, *et al.* Irrigation in the age of agriculture 4.0: management, monitoring and precision. *Revista Ciência Agronômica*. 2020;51:e20207695.
 14. Mallareddy M, Thirumalaikumar R, Balasubramanian P, Naseeruddin R, Nithya N, Mariadoss A, *et al.* Maximizing water use efficiency in rice farming: a comprehensive review of innovative irrigation management technologies. *Water*. 2023;15(10):1802.
 15. Kumar S, Yadav A, Kumar A, Hasanain M, Shankar K, Karan S, *et al.* Climate smart irrigation practices for improving water productivity in India: a comprehensive review. *International Journal of Environment and Climate Change*. 2023;13(12):333-348.
 16. Kundu A, Waris S, Sanam S, Aslam H, Khan B, Bogati SK, *et al.* Precision irrigation systems for sustainable water management in maize cultivation: impact on yield and water use efficiency. *Indus Journal of Bioscience Research*. 2025;3(1):85-94.
 17. Yaqoob N, Farooque AA, Shah SHH, Abbas F, Hassan M. Variable rate irrigation through digital agriculture for sustainable water management: a meta review on current challenges and future directions. *Water Resources Management*. 2026;40(6):237.
 18. Silva M. Water use efficiency in precision agriculture: a study on European farming practices. *Management*. 2025;1(01).
 19. Jiménez AF, Cárdenas PF, Jiménez F. Intelligent IoT-multiagent precision irrigation approach for improving water use efficiency in irrigation systems at farm and district scales. *Computers and Electronics in Agriculture*. 2022;192:106635.
 20. Gupta S, Chowdhury S, Govindaraj R, Amesho KT, Shangdiar S, Kadhila T, *et al.* Smart agriculture using IoT for automated irrigation, water and energy efficiency. *Smart Agricultural Technology*. 2025;12:101081.
 21. Liang Z, Liu X, Xiong J, Xiao J. Water allocation and integrative management of precision irrigation: a systematic review. *Water*. 2020;12(11):3135.
 22. Aarif KOM, Alam A, Hotak Y. Smart sensor technologies shaping the future of precision agriculture: recent advances and future outlooks. *Journal of Sensors*. 2025;2025(1):2460098.
 23. Bellvert J, Mata M, Vallverdú X, Paris C, Marsal J. Optimizing precision irrigation of a vineyard to improve water use efficiency and profitability by using a decision-oriented vine water consumption model. *Precision Agriculture*. 2021;22(2):319-341.
 24. Kim TH, AlZubi AA. AI-enhanced precision irrigation in legume farming: optimizing water use efficiency. *Legume Research: An International Journal*. 2024;47(8).
 25. Galal YGM, Soliman SM. Soil and water management by climate smart and precision agriculture systems under arid climate. In: *Managing Soil Drought*. Boca Raton, FL: CRC Press; 2024. p. 310-361.
 26. González Perea R, Daccache A, Rodríguez Díaz JA, Camacho Poyato E, Knox JW. Modelling impacts of precision irrigation on crop yield and in-field water management. *Precision Agriculture*. 2018;19(3):497-512.
 27. Patidar A, Chaudhary R, Mishra N, Rajpoot SK, Prasad SK, Bhushan C. Smart water systems: AI and IoT in precision irrigation. In: *Sustainable Agriculture Management in Semi-Arid Climates*. Vol 2. Cham: Springer Nature Switzerland; 2025. p. 175-193.
 28. Raut V, Sheikh I, Visvaas R. Field evaluation of smart irrigation systems designed for precision agriculture to optimize water use efficiency and crop yield. *VW Engineering International*. 2025;6(1).
 29. García L, Parra L, Jimenez JM, Lloret J, Lorenz P. IoT-based smart irrigation systems: an overview on the recent trends on sensors and IoT systems for irrigation in precision agriculture. *Sensors*. 2020;20(4):1042.
 30. Munyaradzi M, Hapanyengwi G, Masocha M, Mutandwa E, Raeth P, Nyambo B, *et al.* Precision irrigation scheduling based on wireless soil moisture sensors to improve water use efficiency and yield for winter wheat in Sub-Saharan Africa. *Advances in Agriculture*. 2022;2022(1):8820764.
 31. Kadyampakeni DM, Scudiero E, Shrestha R. Advances in precision irrigation management in the twenty-first century. *Irrigation Science*. 2025;43(5):989-994.
 32. Abioye EA, Hensel O, Esau TJ, Elijah O, Abidin MSZ, Ayobami AS, *et al.* Precision irrigation management using machine learning and digital farming solutions. *AgriEngineering*. 2022;4(1):70-103.
 33. Kamiński C, Soininen JP, Taumberger M, Dantas R, Toscano A, Salmon Cinotti T, *et al.* Smart water management platform: IoT-based precision irrigation for agriculture. *Sensors*. 2019;19(2):276.
 34. Sikka AK, Islam A, Rao KV. Climate-smart land and water management for sustainable agriculture. *Irrigation and Drainage*. 2018;67(1):72-81.
 35. Barua A, Rahaman M. Development of precision irrigation system in agriculture. In: *Integrated and Sustainable Agricultural Practices*. p. 86.
 36. Nikolaou G, Neocleous D, Christou A, Kitta E, Katsoulas N. Implementing sustainable irrigation in water-scarce regions under the impact of climate change. *Agronomy*. 2020;10(8):1120.
 37. Belghachi M. Smart irrigation systems using AI to optimize

- water usage. In: Cases on AI-Driven Solutions to Environmental Challenges. IGI Global Scientific Publishing; 2025. p. 241-268.
38. Kumar SV, Jeberson W, Kumar IR. Internet-of-Things (IoT)-based smart agriculture and precision irrigation for agriculture: an intelligent water management. Yugoslav Journal of Operations Research. 2025;(00):14-14.
 39. Bindu S, Paikra PS, Sharma SK, Meena NK. Water-smart agriculture: efficient irrigation and water conservation technologies.
 40. Anjum MN, Cheema MJM, Hussain F, Wu RS. Precision irrigation: challenges and opportunities. In: Precision Agriculture. 2023. p. 85-101.
 41. Tabassum M. Precision irrigation scheduling using real-time environmental data. International Journal on Computational Modelling Applications. 2024;1(2):20-34.
 42. Shi J, Wu X, Zhang M, Wang X, Zuo Q, Wu X, *et al.* Numerically scheduling plant water deficit index-based smart irrigation to optimize crop yield and water use efficiency. Agricultural Water Management. 2021;248:106774.
 43. King BA, Shellie KC. A crop water stress index based Internet of Things decision support system for precision irrigation of wine grape. Smart Agricultural Technology. 2023;4:100202.
 44. Bwire D, Watanabe F, Suzuki S, Suzuki K. Improving irrigation water use efficiency and maximizing vegetable yields with drip irrigation and poly-mulching: a climate-smart approach. Water. 2024;16(23):3458.
 45. Thorp KR, Calleja S, Pauli D, Thompson AL, Elshikha DE. Agronomic outcomes of precision irrigation management technologies with varying complexity. Journal of the ASABE. 2022;65(1):135-150.
 46. Garcia LD, Lozoya C, Favela-Contreras A, Giorgi E. A comparative analysis between heuristic and data-driven water management control for precision agriculture irrigation. Sustainability. 2023;15(14):11337.
 47. Askaraliev B, Musabaeva K, Koshmatov B, Omurzakov K, Dzhakshylykova Z. Development of modern irrigation systems for improving efficiency, reducing water consumption and increasing yields. Machinery and Energetics. 2024;15(3).
 48. Adeyemi O, Grove I, Peets S, Norton T. Advanced monitoring and management systems for improving sustainability in precision irrigation. Sustainability. 2017;9(3):353.