

## Recent Advances in Agricultural Precision Irrigation Method Based on Intelligent Control Algorithm

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**Abstract.** As the global water shortage problem is becoming more and more serious, precision irrigation in agriculture has become a key technology to improve the efficiency of water utilization, guarantee food security and environmental protection. The continuous development of intelligent control algorithms provides new solutions for agricultural precision irrigation. This paper systematically analyzes the research status, technical applications, problems and future development trends of agricultural precision irrigation methods based on intelligent control algorithms through literature review. It is found that a variety of intelligent control algorithms show broad application prospects in agricultural precision irrigation, but still face some technical challenges and practical application limitations. Future research should further optimize the performance of algorithms, strengthen the integration of multiple technologies, and promote the popularization and application of smart irrigation technology.

**Keywords:** *intelligent control algorithms; reinforcement learning; precision irrigation in agriculture; fuzzy control*

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### Introduction

In the context of increasing global water scarcity, agriculture is a major water consumer, and the traditional irrigation method is difficult to meet the needs of sustainable development due to inefficiency and serious waste [1]. Precision irrigation technology has emerged, which realizes the precision and automation of irrigation based on the actual water demand of crops and soil moisture status, effectively improves the efficiency of water use, reduces waste, and lowers the cost of agricultural production [2]. The rise of intelligent control algorithms provides strong technical support for precision irrigation, and algorithms such as fuzzy control, neural networks, genetic algorithms, etc. can accurately deal with complex farmland environmental information and formulate scientific and reasonable irrigation strategies [3]. These algorithms can not only optimize the irrigation process, but also deeply integrate with the Internet of Things, big data, cloud computing and other cutting-edge technologies to build an intelligent irrigation system and achieve efficient water conservation and intelligent management of agricultural production [4-6].

Precision irrigation technology has significant practical significance and potential value, which is mainly reflected in three aspects: first, water conservation and efficiency, precision irrigation through precise control of irrigation volume, to avoid water waste, improve water productivity, to protect the yield and quality of crops [7]; second, ecological and environmental protection, to reduce the amount of water used for irrigation, to reduce the risk of soil erosion and nutrient loss, to prevent soil salinization and water pollution, to protect the ecological environment [8]; Third, reduce production costs, precision irrigation can automatically control irrigation according to soil and crop demand, reduce labor input, realize automation and intelligent management of agricultural production, and improve agricultural production efficiency [9].

Current research in precision irrigation focuses on intelligent irrigation system design and optimization [10], application and improvement of intelligent control algorithms [11], and multi-technology integration [12]. Intelligent irrigation system design and optimization includes the integration of irrigation system modules, the improvement of functional domain performance, and the development of intelligent irrigation schemes [13]; the application and improvement of intelligent control algorithms is to study how to better apply intelligent control algorithms, such as fuzzy control, neural networks, and intelligent optimization algorithms, to precise irrigation decision-making, and to improve the precision and efficiency of irrigation control [14]; and to explore intelligent control algorithms and Internet of Things, big data, cloud computing and other technology integration methods to build a more intelligent and efficient precision irrigation system [15].

Current research has made significant progress in the field of precision irrigation, and the application of intelligent control algorithms has made irrigation decision-making more scientific and precise, and the integration of multiple technologies has further improved the intelligence of irrigation systems [16]. Fuzzy control algorithms are highly subjective due to their reliance on expert experience, which makes it difficult to adapt to the complex and changing farmland environment [17]; neural network algorithms require a large amount of data training, which has high requirements on data quality and quantity, and insufficient data or the presence of noise affects the accuracy of the model prediction [18]; intelligent optimization algorithms, although they have the ability to perform global searches, have the problems of precocious convergence and high computational volume, which affect the optimization effect of the irrigation plan [19]. The exploration of multi-technology integration is still in the primary stage, and in-depth research is needed to realize closer and more efficient integration [20].

## Agricultural precision irrigation system design

### Irrigation system module

Agricultural precision irrigation system is mainly composed of data acquisition module, data transmission module, data processing module, control execution module, data management module, etc [22], the main description and role of each module is shown in Table 1.

**Table 1.** Description of Agricultural Irrigation System Modules

No.	Module	Description
1	Data Acquisition Module	Responsible for real-time monitoring of farmland environmental parameters and crop growth status
2	Data Transfer Module	The acquired information is transferred to the data processing module
3	Data processing module	Analyze and process the collected data
4	Control Actuator Module	Control the operation of irrigation equipment based on the results of decision-making
5	Data management module	Storage, management and analysis of large amounts of irrigation data

### Data acquisition module

The data acquisition module is the basis of the precision irrigation system, which is responsible for real-time monitoring of farmland environmental parameters and crop growth status [23]. This module usually includes a variety of sensors, such as soil moisture sensors, soil temperature sensors, weather stations (to monitor air temperature, humidity, wind speed, rainfall, etc.), light sensors, and sensors to monitor crop growth status (e.g., leaf area index sensors, plant water potential sensors, etc.) [24-26]. These sensors transmit the collected data to the central control system through IoT technology [27]. The sensor types and related parameters are shown in Table 2.

**Table 2.** Sensor type parameters

Sensor types	Measurement range	accurate	resolution (of a photo)	Applicable environment
Soil Moisture Sensor	0%–100%	±3%	0.1%	Various types of soil
Soil temperature sensors	-20°C–100°C	±0.5°C	0.1°C	Various types of soil
Meteorological stations (air temperature)	-40°C–70°C	±0.5°C	0.1°C	Outdoor open environment
Meteorological stations (air humidity)	0%–100%	±3%	0.1%	Outdoor open environment
Weather stations (wind speed)	0–30 m/s	±0.5 m/s	0.1 m/s	Outdoor open environment
Meteorological stations (rainfall)	0–100 mm/h	±1 mm	0.1 mm	Outdoor open environment
Light Sensor	0–200,000 lux	±5%	1 lux	Outdoor and greenhouse environments
Leaf Area Index Sensor	0–10	±0.2	0.01	crop canopy
Plant Water Potential Sensor	-2 MPa–0 MPa	±0.1 MPa	0.01 MPa	Crop Root Zone

### Data transmission module

The data transmission module is responsible for transferring the information acquired by the data acquisition module to the data processing module. Common transmission methods include wired transmission and wireless transmission [28]. Wired transmission usually uses communication protocols such as RS485 and is suitable for short-distance transmission. Wireless transmission includes technologies such as NB-IoT, LoRa, and Wi-Fi, which are suitable for long-distance transmission and complex terrain [29-30]. A comparison of data transmission technologies is shown in Table 3.

**Table 3.** Comparison results of data transmission technologies

Transmission technology	Distance	Rate	Power wastage	Dependability	Costs
RS485	1000 m	100 kbps	center	your (honorific)	lower (one's head)
NB-IoT	10 km+	100 kbps	lower (one's head)	your (honorific)	center
LoRa	5–15 km	50 kbps	lower (one's head)	center	center
Wi-Fi	100 m	100 Mbps	center	center	lower (one's head)

### Data processing module

The data processing module is the control center of the system, responsible for analyzing and processing the collected data. This module is usually implemented based on cloud computing platforms or local servers, and uses intelligent control algorithms [31-32] (e.g., fuzzy control algorithms, neural network algorithms, genetic algorithms, etc.) to analyze the data and make irrigation decisions.

### Control execution module

The control execution module controls the operation of irrigation equipment based on the decisions of the data processing module, and its core functions include controlling the startup and shutdown of water pumps, adjusting the opening and closing degrees of valves, and controlling the amount of water used for irrigation [33]. This module ensures the precise execution of the irrigation strategy by linking with the irrigation equipment (e.g., water pumps, solenoid valves, etc.) [34].

### Data management module

The data management module is responsible for storing, managing and analyzing a large amount of irrigation data. This module is usually implemented based on a database management system, which supports the query and analysis of historical data and provides data support for the long-term operation and optimization of the system [35].

### Functional performance analysis of irrigation systems

The functional performance of the irrigation system based on intelligent control algorithm mainly includes monitoring function, decision-making function, control function and data management function [36], which are analyzed as shown in Table 4.

**Table 4. System Functional Performance Analysis**

No.	Functionality	Performances	Object
1	monitoring function	Accuracy and timeliness	transducers
2	decision function	Accuracy and timeliness	Intelligent control algorithms
3	control function	Accuracy and adaptability	Irrigation equipment
4	control function	Efficient storage, fast query and deep analysis capabilities	Storage Module

As can be seen from Table 4, the functions of the intelligent irrigation system are reflected as follows: 1) The performance of the monitoring function is mainly reflected in the accuracy and timeliness of the data. High-precision sensors can provide reliable monitoring data, while efficient transmission and processing mechanisms ensure real-time data. The accuracy of monitoring data directly affects the scientificity of irrigation decision-making; 2) The performance of the decision-making function depends on the accuracy and adaptability of the intelligent control algorithm. Excellent algorithms can comprehensively consider a variety of factors to develop an optimal irrigation strategy. At the same time, the adaptability of the algorithm makes it possible to quickly adjust the decision-making when the environment changes to ensure the irrigation effect; 3) The performance of the control function is mainly reflected in the accuracy and stability of the control. Accurate control ensures that the irrigation equipment operates according to the predetermined strategy, avoiding the waste of water resources and over-irrigation. Stable control ensures the long-term reliable operation of the system; 4) The performance of the data management function is reflected in the efficient storage, rapid query and in-depth analysis ability of the data. The efficient storage mechanism ensures data security and integrity, the fast query capability supports users' real-time data needs, and the in-depth analysis provides support for system optimization. Based on the above functional analysis, the system specific index performance is shown in Table 5.

**Table 5. System performance metrics analysis**

Performance Metric	Unit	Evaluation Method	Importance
Irrigation Efficiency	%	Output/Input	Water and energy efficiency
Uniformity	%	Coefficient of variation method	Crop growth consistency
System Reliability	Times per year	Statistics of failure frequency	Maintenance requirements and costs
Response Time	Minutes	From instruction to execution	System efficiency
Data Accuracy	%	Comparison with field measurements	Decision-making quality
Usability	-	User satisfaction survey	User interaction experience
Scalability	-	Ability to add new modules	System upgrades and future expansion
Cost-Benefit Ratio	Yuan per acre	Total cost/Covered area	Return on investment and economic feasibility

## Intelligent irrigation control program

### Design Program

The design of a precision irrigation system for agriculture is a complex multi-step process, and in conjunction with the previous discussion, this section gives a general design of an intelligent scheme for irrigation control, as shown in Table 6.

**Table 6. Irrigation Control Intelligent Program**

No.	Step	Objective
1	Requirement Analysis	Clarify irrigation requirements and determine system functions and performance metrics
2	System Architecture Design	Build an IoT-based system architecture
3	Sensor Network Deployment	Reasonably deploy sensors
4	Data Transmission Network Construction	Select appropriate communication technology and build a reliable data transmission network
5	Selection and Development of Intelligent Control Algorithm	Choose suitable intelligent control algorithms for water demand prediction
6	Irrigation Strategy Formulation	Formulate initial irrigation strategies and optimize them
7	System Integration and Testing	Create a complete irrigation system and conduct small-scale testing
8	Feedback and Optimization	Continuously adjust and optimize irrigation strategies based on feedback
9	Expansion and Maintenance	Expand and upgrade the system
10	Training and Technical Support	Provide users with training on system usage and maintenance
11	Evaluation and Iteration	Make necessary improvements based on evaluation results

**Program Comparison**

This section focuses on the comparative analysis from the three intelligent scenarios, as shown in Table 7.

**Table 7.** Comparison of Intelligent Solutions

No.	Solution Name	Method Principle
1	Fuzzy Control	Establish fuzzy rule base and use fuzzy inference mechanism
2	Neural Network	Build complex relationship models between inputs and outputs
3	Intelligent Optimization Algorithm	Simulate natural evolution or group behavior to search for optimal solutions

As can be seen from Table 7, the fuzzy control scheme utilizes fuzzy logic to deal with uncertainty and ambiguity information, which is suitable for complex farmland environments, and its advantages include easy to understand and implement, strong robustness, but its rule design relies on experts' experience, which is more subjective [37]; the neural network scheme builds a model of complex relationship between inputs and outputs by learning the historical data, and its advantages include strong nonlinear mapping ability and self-learning ability, but its training process requires a large amount of data and the model interpretation is poor [38]; intelligent optimization algorithms are used to optimize irrigation schedules and control parameters, the advantages include strong global search ability and fast convergence, but there are problems of precocious convergence and large computational volume [39].

**Application of Intelligent Control Algorithm in Agricultural Precision Irrigation**

**Fuzzy control algorithm**

Fuzzy control algorithm is an intelligent control method based on fuzzy logic, which is particularly suitable for dealing with those uncertainties and ambiguous information in precision irrigation in agriculture [40]. In practical applications, the range of variation of parameters such as soil moisture and temperature is often difficult to be defined in terms of precise values, and then fuzzy rules are needed to describe irrigation decisions [41]. A fuzzy rule can be defined as follows: if the soil moisture is “lower” and the temperature is “higher”, the amount of irrigation should be set to “more” [42]. The advantage of this approach is that it is easy to understand and implement and does not require accurate modeling of complex systems.

The fuzzy inference system includes a fuzzification interface, a fuzzy rule base, and a defuzzification interface [43]. The fuzzification interface is responsible for converting precise input data into fuzzy values; the fuzzy rule base stores a series of fuzzy rules for describing the control strategy of the system; and the defuzzification interface converts fuzzy inference results into precise output control signals. In precision irrigation, the fuzzy control algorithm is able to formulate irrigation strategies based on fuzzy information such as soil moisture and temperature, which has the advantages of being easy to understand and implement and robust, but the fuzzy rule design relies on the experience of experts and is highly subjective [44]. The specific steps of the agricultural precision irrigation method based on fuzzy control algorithm are shown in Table 8.

**Table 8.** Steps in the methodology of precision irrigation in agriculture based on fuzzy control algorithm

Step Number	Step	Specific Implementation
1	Fuzzification	Convert precise input values into fuzzy values
2	Establish Fuzzy Rule Base	Define a series of fuzzy rules based on expert experience and domain knowledge
3	Fuzzy Inference	Perform fuzzy inference operations to obtain fuzzy output results
4	Defuzzification	Convert fuzzy inference results into precise output control signals

**Neural Network Algorithm**

Neural network algorithm has shown great potential in the field of precision irrigation in agriculture due to its powerful nonlinear mapping ability and self-learning capability [45]. It is able to build an accurate prediction model by learning and training a large amount of historical irrigation data and capturing complex patterns of relationships between inputs and outputs [46]. With inputs such as meteorological data, soil moisture data, and crop growth stages, neural networks can be trained to predict crop water requirements for a future period of time [47].

In precision irrigation, neural networks are used to predict crop water requirements, simulate changes in soil moisture dynamics, and optimize irrigation control strategies [48]. These applications have greatly improved the science and accuracy of irrigation decisions. However, the limitations of the algorithm are mainly reflected in the dependence on training data. If the training data are noisy or incomplete, it may affect the prediction accuracy of the model [49].

The commonly used types of neural networks and their characteristics are shown in Table 9.

**Table 9.** Neural network characteristics and applications

Type	Advantages	Disadvantages	Application Scenarios
Multilayer Perceptron	Capable of handling complex nonlinear relationships and high prediction accuracy	Training process may be slow and prone to overfitting	Suitable for various irrigation prediction and control tasks
Radial Basis Function Network	Fast learning speed and good generalization ability	Sensitive to parameter selection and may not perform well on large-scale data	Used for quick prediction of crop water demand
Convolutional Neural Network	Strong automatic feature extraction and high prediction accuracy	May perform poorly on non-image data and requires high computational resources	Suitable for irrigation decision-making support based on soil image analysis
Recurrent Neural Network	Can capture temporal dependencies and is suitable for dynamic prediction	High training complexity and may face gradient vanishing problems	Used for predicting dynamic changes in crop water demand

### Intelligent Optimization Algorithm

Intelligent optimization algorithms are a class of advanced algorithms that perform search and optimization by simulating natural phenomena or biological behavior. In the field of precision irrigation, these algorithms are widely used to optimize irrigation schedules and control parameters [50-53].

Genetic algorithm (GA) simulates the biological evolution process to continuously optimize the irrigation scheme through selection, crossover and mutation operations [54]. It is capable of gradually screening out the optimal scheme from a large number of possible irrigation schemes to maximize irrigation efficiency and optimal use of water resources.

Ant colony algorithm (ACO) simulates the foraging behavior of ants to find the optimal irrigation network path and resource allocation scheme through the accumulation of pheromones [55-56]. In irrigation systems, ACO can effectively optimize the layout of the irrigation network and the allocation of water resources to improve irrigation efficiency and reduce water waste.

Particle Swarm Optimization (PSO) algorithm searches for optimal solutions in the solution space by simulating the flight behavior of a flock of birds. It excels in optimizing irrigation control parameters and scheduling schemes. In multi-source irrigation systems, PSO can be used to optimize the timing and distribution of water supply from each source [57].

### Reinforcement Learning and Deep Reinforcement Learning

Reinforcement learning is a machine learning method in which an intelligent body learns the optimal strategy to maximize the cumulative reward by interacting with the environment. In precision irrigation, the intelligent body selects the optimal irrigation operation based on the current environmental information such as soil moisture and crop growth status. The intelligent body can choose to turn on or off the irrigation equipment, or adjust the irrigation time [58]. Through continuous trial and learning, the intelligent body can master the optimal irrigation strategy under different environmental conditions, thus realizing precise irrigation [59].

Deep reinforcement learning combines the advantages of deep learning and reinforcement learning by using neural networks to approximate the policy function and value function. It is able to handle more complex state and action spaces and improve the accuracy of irrigation control [60]. The deep Q network (DQN) is used to learn the state-action value function of the irrigation environment to realize intelligent control of irrigation equipment and improve irrigation efficiency and crop yield. This method realizes intelligent control of irrigation equipment

by constructing a deep Q network (DQN) and learning the state-action value function of the irrigation environment [61-63].

The comparison between reinforcement learning and deep reinforcement learning is shown in Table 10.

**Table 10.** Comparison of reinforcement learning and deep reinforcement learning

Feature/Algorithm Type	Reinforcement Learning	Deep Reinforcement Learning
State Space Handling	Usually handles finite or moderately sized state spaces	Capable of handling high-dimensional and complex state spaces such as images or large amounts of sensor data
Policy Representation	Policies are usually represented in tabular or simple functional forms	Uses deep neural networks to represent policy functions with strong feature extraction and representation capabilities
Training Data Requirement	Relatively small amount of training data is sufficient to start learning	Requires large amounts of training data with higher data collection and storage costs
Training Time	Relatively short training time	Long training time requiring more computational resources
Generalization Ability	Limited generalization ability and may perform poorly on unseen states	Better generalization ability and adapts well to new situations in the state space
Application Scenarios	Suitable for irrigation scenarios with relatively simple state and action spaces	Suitable for precision irrigation control in complex dynamic environments such as multi-water-source or multi-crop systems
Irrigation Control Accuracy	Moderate irrigation control accuracy suitable for general irrigation needs	High accuracy enabling more refined irrigation control and improved water resource utilization efficiency

## Integration of intelligent control algorithms with other technologies

### Integration with IoT technologies

Internet of Things (IoT) technology provides powerful technical support for agricultural precision irrigation by connecting various devices and sensors to the Internet to realize interconnection between devices and real-time data transmission [64]. In agricultural precision irrigation, IoT technology is mainly applied to data acquisition and transmission, remote monitoring and control, intelligent decision-making and automated management [66-67].

In terms of data collection and transmission, the environmental parameters of the farmland and the growth status of crops can be monitored in real time by deploying a large number of sensor nodes in the farmland, and these sensors will transmit the collected data to cloud servers or local control systems through wireless communication technology [68]; in terms of remote monitoring and control, IoT technology makes it possible for farmers to operate and manage the irrigation equipment without physically going to the farmland site. operation and management, and through IoT technology, farmers can use terminal devices such as smartphones, tablets, or computers to remotely control irrigation system operations such as starting, stopping, and adjusting the irrigation volume [69]; in terms of intelligent decision-making and automated management, the combination of intelligent control algorithms and IoT technology realizes the intelligence and automation of the precision irrigation system, and based on real-time IoT sensors collected real-time data, data analysis and processing, development of optimal irrigation strategies, and remote control of irrigation equipment operation through IoT technology [70]. The comparative analysis of IoT based irrigation technology with traditional irrigation technology is shown in Table 11.

**Table 11.** Comparison of IoT-based irrigation technologies with traditional irrigation technologies

Technology Type	Data Collection Method	Data Transmission Method	Control Method	Irrigation Efficiency	Cost
IoT Technology	Automatic sensor data collection	Wireless transmission	Remote automatic control	High	Medium
Traditional Irrigation Technology	Manual inspection data collection	None	Local manual control	Low	Low

### Integration with big data and cloud computing technologies

Big data and cloud computing technologies provide rich data support and in-depth analytical capabilities for precision irrigation in agriculture by collecting, storing, managing, and analyzing massive amounts of data [71]. In precision irrigation, big data and cloud computing technologies are mainly applied to data collection and

integration, data analysis and mining, prediction and decision support, computation and analysis, application services and decision support [72-73].

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**Table 12.** Comparison of Big Data and Cloud Computing Technologies in Precision Irrigation

Technical Application	Big Data Technology	Cloud Computing Technology
Data Collection and Integration	Collect and integrate massive sensor data to establish centralized data warehouses	Provide distributed storage and computing resources to support large-scale data storage and processing
Data Analysis and Mining	Use data analysis algorithms to discover irrigation patterns and crop growth rules	Provide powerful computing capabilities to quickly process complex data analysis tasks
Prediction and Decision Support	Build prediction models to forecast crop water demand and irrigation effects	Provide real-time computation support to quickly generate irrigation decision recommendations
Application Services and Decision Support	Provide data query and analysis services to support farmers' decisions	Provide cloud-based applications for remote monitoring and intelligent control

## Problems and challenges

According to the current status of research and integration of agricultural precision intelligent control algorithms, the problems and challenges are analyzed as follows:

### Algorithm performance and accuracy need to be improved

Although various intelligent control algorithms have achieved certain results in agricultural precision irrigation, some algorithms still suffer from unstable performance, low accuracy, and poor adaptability in complex and changing agricultural environments [82-83]. Neural network algorithms require high quality and quantity of training data, which may affect the prediction accuracy of the model if the data are noisy or incomplete.

### Difficulty in acquiring and processing data

The application of intelligent control algorithms relies on a large amount of farm data, such as soil moisture, temperature, nutrient content, and crop growth status. However, in actual agricultural production, data acquisition and processing face many difficulties. On the one hand, the high cost of sensor equipment and the complexity of deployment and maintenance lead to limitations in the range and frequency of data acquisition; on the other hand, the transmission, storage and processing of data require strong technical support, and there are challenges in data quality assurance and security management.

### Complexity of multi-technology integration

When deeply integrating intelligent control algorithms with IoT, big data, cloud computing and other technologies, they face problems such as technical compatibility, inconsistent data formats, and differences in communication protocols [84]. IoT devices from different vendors may use different communication protocols and data formats, resulting in data that cannot be directly docked and shared, increasing the difficulty of system integration.

## Conclusion

This paper provides a systematic review of agricultural precision irrigation methods based on intelligent control algorithms, and draws the following conclusions: the application of intelligent control algorithms in agricultural precision irrigation provides an effective technical means to improve irrigation efficiency, conserve water resources and promote the sustainable development of agriculture. A variety of intelligent control algorithms (e.g., fuzzy control algorithms, neural network algorithms, intelligent optimization algorithms, etc.) show broad application prospects in precision irrigation, but still face some problems and challenges, such as algorithmic

performance and accuracy need to be improved, the difficulty of data acquisition and processing, and the low level of cognition and acceptance of farmers and technicians.

Future research should focus on the following aspects: 1) improving the adaptability and accuracy of the algorithm in complex agricultural environments by improving the algorithm structure, optimizing the parameter settings, and introducing new learning mechanisms, etc.; and 2) further strengthening the integration of intelligent control algorithms with the Internet of Things (IoT), Big Data, Cloud Computing, and Satellite Remote Sensing, etc., so as to realize the data sharing and collaborative work, and to improve the overall performance of the intelligent irrigation system.

## References

- [1] Dhanke J A, Srivastava D, Menaga D, et al. Climate-Based AI-Powered Precision Irrigation: Sustainably Smart Agriculture Frameworks for Maximum Crop Yields[J]. *Remote Sensing in Earth Systems Sciences*, 2025, 8(1):161-172. DOI:10.1007/s41976-024-00174-4.
- [2] Ingole K, Padole D. An Internet of Things (IoT)-based smart irrigation and crop suggestion platform for enhanced precision agriculture[J]. *Journal of information and optimization sciences*, 2024(4):45.
- [3] Abuzanouneh K I M, Al-Wesabi F N, Albraikan A A, et al. Design of Machine Learning Based Smart Irrigation System for Precision Agriculture[J]. *Computers, Materials & Continua*, 2022, 72(1). DOI:10.32604/cmc.2022.022648.
- [4] Bwambale E, Abagale F K, Anornu G K. Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review[J]. *Agricultural Water Management*, 2022, 260. DOI:10.1016/j.agwat.2021.107324.
- [5] Abdulsalam K A, Babatunde D E, Adebisi J A, et al. A CRITIC-CODAS Approach for Ranking Wireless Communication Technologies in Precision Agriculture: Application to Irrigation System[J]. *Journal of Digital Food, Energy & Water Systems (JD-FEWS)*, 2024, 5(1). DOI:10.36615/tfpnav27.
- [6] Rakibuzzaman M. A Review of Precision Irrigation Water-Saving Technology under Changing Climate for Enhancing Water Use Efficiency, Crop Yield, and Environmental Footprints[J]. *Agriculture*, 2024, 14. DOI:10.3390/agriculture14071141.
- [7] Amos G W V. Design and Evaluation of a Precision Irrigation Tool's Human–Machine Interaction to Bring Water- and Energy-Efficient Irrigation to Resource-Constrained Farmers[J]. *Sustainability*, 2024, 16. DOI:10.3390/su16198402.
- [8] Fathy C, Ali H M. A Secure IoT-Based Irrigation System for Precision Agriculture Using the Expedious Cipher[J]. *Sensors (Basel, Switzerland)*, 2023, 23. DOI:10.3390/s23042091.
- [9] Abuzanouneh K I M, Al-Wesabi F N, Albraikan A A, et al. Design of Machine Learning Based Smart Irrigation System for Precision Agriculture[J]. *Computers, Materials and Continuum (English)*, 2022(7): 16. DOI:10.32604/cmc.2022.022648.
- [10] Benzaouia M, Hajji B, Mellit A, et al. Fuzzy-IoT smart irrigation system for precision scheduling and monitoring[J]. *Computers and electronics in agriculture*, 2023, 215(000):16. DOI:10.1016/j.compag.2023.108407.
- [11] Munyaradzi M, Hapanyengwi G, Masocha M, 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[J]. *Advances in Agriculture*, 2022. DOI:10.1155/2022/8820764.
- [12] Munaganuri R K, Rao Y N. PAMICRM: Improving Precision Agriculture Through Multimodal Image Analysis for Crop Water Requirement Estimation Using Multidomain Remote Sensing Data Samples[J]. *IEEE Access*, 2024:12. DOI:10.1109/ACCESS.2024.3386552.
- [13] Sangeetha S, Indumathi N, Grover R, et al. IoT Based Wireless Communication System for Smart Irrigation and Rice Leaf Disease Prediction Using ResNeXt-50[J]. *International Journal on Artificial Intelligence Tools*, 2024, 33(2). DOI:10.1142/S0218213024500040.
- [14] Premkumar S, Sigappi A. IoT-enabled edge computing model for smart irrigation system[J]. *Journal of Intelligent Systems*, 2022, 31(1):632-650. DOI:10.1515/jisys-2022-0046.
- [15] Yu F, Xu T, Guo Z, et al. Research Status and Prospects of Key Technologies for Rice Smart Unmanned Farms[J]. *Smart Agriculture*, 2024, 6(6):1-22. DOI:10.12133/j.smartag.SA202410018.

- [16] Szabo A, J. Tamás, dám Kvesdi, et al.Evaluation of new pivoting linear - move precision irrigation machine[J].Irrigation and Drainage, 2023.DOI:10.1002/ird.2850.
- [17] Sadak F. A Deep Learning-Based Sensor Modeling for Smart Irrigation System[J].Agronomy, 2022, 12.DOI:10.3390/agronomy12010212.
- [18] Mamun M R A, Ahmed A K, Upoma S M,et al.IoT-enabled solar-powered smart irrigation for precision agriculture[J].Smart Agricultural Technology, 2025, 10.DOI:10.1016/j.atech.2025.100773.
- [19] Peeters A, Cohen Y, Bahat I,et al.A spatial machine-learning model for predicting crop water stress index for precision irrigation of vineyards[J].Computers and Electronics in Agriculture, 2024(Pt.2):227.DOI:10.1016/j.compag.2024.109578.
- [20] Kim T H, Alzubi A A.AI-Enhanced Precision Irrigation in Legume Farming: Optimizing Water Use Efficiency[J]. Legume Research: An International Journal, 2024, 47(8). DOI:10.18805/LRF-791.
- [21] Hamdaoui H, Hsana Y, Hamdi I,et al.Revolutionizing Agriculture: A Comprehensive Review of AI-Enabled Precision Irrigation and Water Quality Forecasting[J].Basrah Journal of Agricultural Sciences, 2024, 37(2).DOI:10.37077/25200860.2024.37.2.26.
- [22] Kakkavou K, Gemtou M, Fountas S.Drivers and barriers to the adoption of precision irrigation technologies in olive and cotton farming—Lessons from Messenia and Thessaly regions in Greece[J].Smart Agricultural Technology, 2024, 7.DOI:10.1016/j.atech.2024.100401.
- [23] Suhardi, Marhaenanto B, Widjaja Putra B T.The Application of Smart Drip Irrigation System for Precision Farming[J].Pertanika Journal of Science & Technology, 2024, 32(6).DOI:10.47836/pjst.32.6.17.
- [24] Garcia L D, Lozoya C, Castaeda H,et al.A discrete sliding mode control strategy for precision agriculture irrigation management[J].Agricultural Water Management, 2025, 309.DOI:10.1016/j.agwat.2025.109315.
- [25] Vasireddy S S D M, Yalagala S, Sikha J,et al.Irrigation in Precision Agriculture Using Blockchain Ethereum Based on IoT[J].Engineering Proceedings, 2024, 66.DOI:10.3390/engproc2024066029.
- [26] Verma S K, Verma A.Precision irrigation management: An innovative technique for efficient water management[J].Indian Farming, 2023, 73(4):21-24.
- [27] Morcillo M, Ortega J F, Ballesteros R,et al.A holistic simulation model of solid-set sprinkler irrigation systems for precision irrigation[J].Precision Agriculture, 2024, 25(6).DOI:10.1007/s11119-024-10171-8.
- [28] Singh D K, Sobti R.Long-range real-time monitoring strategy for Precision Irrigation in urban and rural farming in society 5.0[J].Computers & Industrial Engineering, 2022, 167:107997-.DOI:10.1016/j.cie.2022.107997.
- [29] Singh D, Sobti R, Malik P K,et al.IoT-Driven Model for Weather and Soil Conditions Based on Precision Irrigation Using Machine Learning[J].Security and Communication Networks, 2022.DOI:10.1155/2022/7283975.
- [30] Eswaran U, Eswaran V, Eswaran M V.Precision Agriculture Revolution: A Low-cost Smart Irrigation System Empowered by IoT for Small-scale Farmers[J].Journal of Mechatronics & Automation, 2023, 10(3):21-29.
- [31] Baldi E, Quartieri M, Larocca G N, et al.5. Smart irrigation system for precision water management: effect on yield and fruit quality of yellow fleshed kiwifruit in northern Italy[J]. Precision agriculture '23, 2023.DOI:10.3920/978-90-8686-947-3\_5.
- [32] László Csambalik.Enhancing Precision Agriculture for Climate Change Mitigation in Visegrad Countries: Factors Shaping Adaptation[J]. Land, 2025, 14.DOI:10.3390/land14020399.
- [33] Kang J, Ding R, Chen J,et al.Crop root system phenotyping with high water-use efficiency and its targeted precision regulation: Present and prospect[J].Agricultural Water Management, 2025, 309.DOI:10.1016/j.agwat.2025.109327.
- [34] Brighenti S, Tagliavini M, Comiti F,et al.Drip irrigation frequency leads to plasticity in root water uptake by apple trees[J].Agricultural Water Management, 2024, 298(000):14.DOI:10.1016/j.agwat.2024.108870.
- [35] Pandrea V A, Ciocoiu A O, Machedon-Pisu M.IoT-Based Irrigation System For Agriculture 5.0[J].2023 17th International Conference on Engineering of Modern Electric Systems (EMES), 2023:1-4.DOI:10.1109/EMES58375.2023.10171631.
- [36] Aroonsrimorakot S, Laiphrakpam M.Green innovation to save water and energy for environmental sustainability in agricultural farming: A review[J].Agriculture and Natural Resources, 2023, 57(4):739-748.
- [37] Lipovac A, Canaj K, Mehmeti A,et al.Leveraging Precision Agriculture Principles for Eco-Efficiency: Performance of Common Bean Production Across Irrigation Levels and Sowing Periods[J].Water (20734441), 2025, 17(9).DOI:10.3390/w17091312.

- [38] Bwambale E, Abagale F K, Anornu G K. Data-driven model predictive control for precision irrigation management[J]. *Smart Agricultural Technology*, 2023, 3. DOI:10.1016/j.atech.2022.100074.
- [39] Lakshmi G S P, Asha P, Sandhya G, et al. An intelligent IOT sensor coupled precision irrigation model for agriculture[J]. *Measurement: Sensors*, 2022. DOI:10.1016/j.measen.2022.100608.
- [40] Singh D, Biswal A K, Samanta D, et al. Smart high-yield tomato cultivation: precision irrigation system using the Internet of Things[J]. *Frontiers in Plant Science*, 2023, 14(000):17. DOI:10.3389/fpls.2023.1239594.
- [41] Saha G, Shahrin F, Khan F H, et al. Smart IoT-driven precision agriculture: Land mapping, crop prediction, and irrigation system[J]. *PLoS ONE*, 2025, 20(3). DOI:10.1371/journal.pone.0319268.
- [42] Brar A S, Kaur K, Sindhu V K, et al. Sustainable water use through multiple cropping systems and precision irrigation[J]. *Journal of Cleaner Production*, 2022, 333:130117-. DOI:10.1016/j.jclepro.2021.130117.
- [43] Souza S A, Rodrigues L N. Increased profitability and energy savings potential with the use of precision irrigation[J]. *Agricultural Water Management*, 2022, 270. DOI:10.1016/j.agwat.2022.107730.
- [44] Kumar P, Udayakumar A, Kumar A A, et al. Multiparameter optimization system with DCNN in precision agriculture for advanced irrigation planning and scheduling based on soil moisture estimation[J]. *Environmental monitoring and assessment*, 2022, 195(1):13. DOI:10.1007/s10661-022-10529-3.
- [45] Salcedo-Arancibia F, Martín Gutiérrez, Chavoya A. Design, modeling and in silico simulation of bacterial biosensors for detecting heavy metals in irrigation water for precision agriculture[J]. *Heliyon*, 2024, 10(15). DOI:10.1016/j.heliyon.2024.e35050.
- [46] Zhang F, Tang P, Zhou T, et al. Cloud-Based Framework for Precision Agriculture: Optimizing Scarce Water Resources in Arid Environments amid Uncertainties[J]. *Agronomy*, 2024, 14(1). DOI:10.3390/agronomy14010045.
- [47] Souza S A, Rodrigues L N, Cunha F F D. Assessing the precision irrigation potential for increasing crop yield and water savings through simulation[J]. *Precision Agriculture*, 2022, 24(2):533-559. DOI:10.1007/s11119-022-09958-4.
- [48] Sheline C, Ingersoll S, Amrose S, et al. Sensitivity study of the Predictive Optimal Water and Energy Irrigation (POWEI<sub>r</sub>) controller's schedules for sustainable agriculture systems in resource-constrained contexts[J]. *Computers and electronics in agriculture*, 2024, 226(000):12. DOI:10.1016/j.compag.2024.109230.
- [49] Bahat I, Netzer Y, Grünzweig, José M, et al. How do spatial scale and seasonal factors affect thermal-based water status estimation and precision irrigation decisions in vineyards?[J]. *Precision Agriculture*, 2024, 25(3):1477-1501. DOI:10.1007/s11119-024-10120-5.
- [50] Wang Z, Liu Z, Yuan M, et al. A machine learning-based irrigation prediction model for cherry tomatoes in greenhouses: Leveraging optimal growth data for precision irrigation[J]. *Computers and Electronics in Agriculture*, 2025, 237. DOI:10.1016/j.compag.2025.110558.
- [51] Alejandro Pérez-Pastor. Combined Effects of Deficit Irrigation and Biostimulation on Water Productivity in Table Grapes[J]. *Plants*, 2024, 13. DOI:10.3390/plants13233424.
- [52] Conde G, Guzman S M, Athelly A. Adaptive and predictive decision support system for irrigation scheduling: An approach integrating humans in the control loop[J]. *Computers and Electronics in Agriculture*, 2024:217. DOI:10.1016/j.compag.2024.108640.
- [53] Peddinti S R, Nicolas F, Raij-Hoffman I, et al. Evapotranspiration estimation using high-resolution aerial imagery and pySEBAL for processing tomatoes[J]. *Irrigation Science*, 2025, 43(1). DOI:10.1007/s00271-024-00943-5.
- [54] Tulu B B, Teshome F, Ampatzidis Y, et al. AgriSenAI: Automating UAV thermal and multispectral image processing for precision agriculture[J]. *SoftwareX*, 2025, 30(000). DOI:10.1016/j.softx.2025.102083.
- [55] Ennatiqi L, Bouziani M, Yaagoubi R, et al. Soqia: A Responsive Web Geographic Information System Solution for Dynamic Spatio-Temporal Monitoring of Soil Water Status in Arboriculture[J]. *AgriEngineering*, 2024, 6(1). DOI:10.3390/agriengineering6010042.
- [56] Soulis K, Dosiadis E, Nikitakis E, et al. Assessing AgERA5 and MERRA-2 Global Climate Datasets for Small-Scale Agricultural Applications[J]. *Atmosphere*, 2025, 16. DOI:10.3390/atmos16030263.
- [57] Li M, Zhang X, Chen Y, et al. Multiobjective optimization of daily scale irrigation schedules for rice in irrigation districts considering joint uncertainties in water supply and demand[J]. *Computers & Electronics in Agriculture*, 2025, 231(000). DOI:10.1016/j.compag.2025.110054.
- [58] Sakthipriya S, Naresh R. Precision agriculture: crop yields classification techniques in thermo humidity sensors[J]. *Optical and quantum electronics*, 2024(3):56. DOI:10.1007/s11082-023-05907-1.

- [59] Xing Y, Wang X. Precision Agriculture and Water Conservation Strategies for Sustainable Crop Production in Arid Regions[J]. *Plants*, 2024, 13. DOI:10.3390/plants13223184.
- [60] Zuckerman N, Cohen Y, Alchanatis V, et al. Toward Precision Agriculture in Outdoor Vertical Greenery Systems (VGS): Monitoring and Early Detection of Stress Events[J]. *Remote Sensing*, 2024, 16(2). DOI:10.3390/rs16020302.
- [61] Ge Y, Liu R, Cao L, et al. Research on ACPS Architecture of Precision Prataculture: A Case of Water Precision Regulation for Alfalfa[J]. *Journal of the ASABE*, 2023. DOI:10.13031/ja.15099.
- [62] Togneri R, Prati R, Nagano H, et al. Data-driven water need estimation for IoT-based smart irrigation: A survey[J]. *Expert Systems with Applications*, 2023, 225(000):22. DOI:10.1016/j.eswa.2023.120194.
- [63] Huang H, Song Y, Fan Z, et al. Estimation of walnut crop evapotranspiration under different micro-irrigation techniques in arid zones based on deep learning sequence models[J]. *Results in Applied Mathematics*, 2023, 20. DOI:10.1016/j.rinam.2023.100412.
- [64] Sengupta P. Can Precision Agriculture Be the Future of Indian Farming?—A Case Study across the South-24 Parganas District of West Bengal, India[J]. *Biology and Life Sciences Forum*, 2023, 30. DOI:10.3390/IOAG2023-16680.
- [65] Langemeier M. Exploring Barriers to the Adoption of Internet of Things-Based Precision Agriculture Practices[J]. *Agriculture*, 2023, 13. DOI:10.3390/agriculture13010163.
- [66] Bondesan L, Ortiz B V, Morlin F, et al. A comparison of precision and conventional irrigation in corn production in Southeast Alabama[J]. *Precision Agriculture*, 2023, 24(1):40-67. DOI:10.1007/s11119-022-09930-2.
- [67] Muroyiwa G S, Mashonjowa E, Raeth M P G. Estimating crop water requirements for irrigation scheduling of tomato using Aquacrop 5.0 and Cropwat 8.0 models under scarcity and unreliability of rainfall in Harare[J]. *African Journal of Agricultural Research*, 2022, 18(12):1089-1101.
- [68] Junpunya M, Ouudomying B, Amornsakchai T, et al. Study of porous rubber pipes reinforced with waste tire fiber and pineapple leaf fiber for smart irrigation system[J]. *IOP Conference Series: Materials Science and Engineering*, 2022. DOI:10.1088/1757-899X/1234/1/012004.
- [69] Hejl R, Straw C, Wherley B, et al. Factors leading to spatiotemporal variability of soil moisture and turfgrass quality within sand-capped golf course fairways[J]. *Precision Agriculture*, 2022, 23(5):1908-1917. DOI:10.1007/s11119-022-09912-4.
- [70] Dahane A, Benameur R, Kechar B. An IoT Low-Cost Smart Farming for Enhancing Irrigation Efficiency of Smallholders Farmers[J]. *Wireless Personal Communications*, 2022, 127(4):3173-3210. DOI:10.1007/s11277-022-09915-4.
- [71] Paudel G, Khanal A, Rahut D, et al. Smart Precision Agriculture but Resource Constrained Farmers: Is service provision a potential solution? Farmer's willingness to pay for laser-land leveling services in Nepal[J]. *Smart Agricultural Technology*, 2022. DOI:10.1016/j.atech.2022.100084.
- [72] Guo J, Bai Q, Guo W, et al. Soil moisture content estimation in winter wheat planting area for multi-source sensing data using CNNR[J]. *Computers and Electronics in Agriculture*, 2022, 193:106670-. DOI:10.1016/j.compag.2021.106670.
- [73] Guo J, Bai Q, Guo W, et al. Soil moisture content estimation in winter wheat planting area for multi-source sensing data using CNNR[J]. *Comput. Electron. Agric.* 2022, 193: 106670. DOI: 10.1016/j.compag.2021.106670.
- [74] Swamidason I T J, Pandiyarajan S, Velswamy K, et al. Futuristic IoT based Smart Precision Agriculture: Brief Analysis[J]. *J. Mobile Multimedia*, 2022, 18:935-956. DOI:10.13052/jmm1550-4646.18323.
- [75] Bonakdari H. NDMI-Derived Field-Scale Soil Moisture Prediction Using ERA5 and LSTM for Precision Agriculture[J]. *Sustainability*, 2025, 17. DOI:10.3390/su17062399.
- [76] Vanderlinden K, Martínez, G, Ramos M, et al. Relevance of NDVI, soil apparent electrical conductivity and topography for variable rate irrigation zoning in an olive grove[J]. *Precision Agriculture*, 2024, 25(6). DOI:10.1007/s11119-024-10191-4.
- [77] J. M. Ramírez-Cuesta, M. A. Martínez-Gimeno, Badal E, et al. UAV-based multispectral and thermal indexes for estimating crop water status and yield on super-high-density olive orchards under deficit irrigation conditions[J]. *Precision Agriculture*, 2025, 26(3). DOI:10.1007/s11119-025-10240-6.
- [78] Mali S S, Scobie M, Baillie J, et al. Integrating UAV-based multispectral and thermal infrared imageries with machine learning for predicting water stress in winter wheat[J]. *Precision Agriculture*, 2025, 26(3). DOI:10.1007/s11119-025-10239-z.

- [79] Hansen N, Flint E, Hopkins A, et al.32. On-farm evaluation of variable rate irrigation for winter wheat in semi-arid western USA[J]. Precision agriculture '23, 2023.DOI:10.3920/978-90-8686-947-3\_32.
- [80] Bueno M, Roel A, Faria L,et al.Land-forming for irrigation (LFI) on a lowland soil protects rice yields while improving irrigation distribution uniformity[J].Precision Agriculture, 2023.DOI:10.1007/s11119-022-09946-8.
- [81] Kerry R, Ingram B, Henrie A, et al.33. Assessing the ability of ECa and drone data to capture spatial patterns in soil moisture for more precise turfgrass irrigation[J]. Precision agriculture '23, 2023.DOI:10.3920/978-90-8686-947-3\_33.
- [82] Toscano F, Fiorentino C, Capece N,et al.Unmanned Aerial Vehicle for Precision Agriculture: A Review[J].IEEE Access, 2024, 12(000):18.DOI:10.1109/ACCESS.2024.3401018.
- [83] Medina D E, Medina J D, Zorro J A,et al.A precision agriculture solution for water stress estimation in Hass avocado farms in Colombia[J].Scientific Reports, 2024, 14(1).DOI:10.1038/s41598-024-82344-4.
- [84] Rashid A B, Kausik A K, Khandoker A,et al.Integration of Artificial Intelligence and IoT with UAVs for Precision Agriculture[J].Hybrid Advances, 2025, 10.DOI:10.1016/j.hybadv.2025.100458.