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Review of Knowledge-Based Management System for Irrigation Scheduling Modeled Upon Reduced Parametric Estimates

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ABSTRACT

Irrigation scheduling is the process of ensuring appropriate, adequate and proportionate crops. Water Management (CWM) stands very important for its water management capability and crop yield optimization among several other advantages. Efficient water management is always crucial for sustainable agricultural practices, traditional irrigation methods often lead to water wastage and suboptimal crop yields Hence, the adoption of technological advancement that spans from the traditional and manual mode to automation, to the application of IOT and extends to the use of Artificial Intelligence (AI). The review paper considers using knowledge-based algorithms for irrigation scheduling, focusing on those that need fewer input parameters. The review looks at several different kinds of knowledge-based algorithms, such as Fuzzy Logic Control, Expert Systems, Neural Networks, Genetic Algorithms, Decision Trees, and Reinforcement learning. The review highlights the fact that knowledge-based algorithms could be a great alternative to traditional irrigation scheduling models, especially when it comes to places where there are few resources for computing power or getting the right data. It also talks about the challenges that come with using these algorithms. Overall, the review makes a strong case for using knowledge-based algorithms for irrigation scheduling. It discusses the tools and techniques used to make these algorithms work well and offers some advice on how to ensure they're being used in the best possible way.

Keywords: *Knowledge-based irrigation algorithms, Sustainable water management, Artificial intelligence in agriculture*

INTRODUCTION

Computational irrigation scheduling methods have been used to optimize water use and crop productivity in agricultural systems. Traditional irrigation scheduling methods are often complex, data-intensive, and computationally demanding, limiting their practical applicability. Research proposes an alternative approach based on knowledge-based algorithms and reduced parametric estimations for irrigation scheduling. The goal is to develop a more efficient and practical method for making irrigation decisions, especially in scenarios where data is scarce. With traditional irrigation methods leading to inefficiency in water use and unnecessary practices, the agricultural sector is becoming increasingly concerned about water scarcity, as mentioned Li *et al.* (2018); Borsato *et al.* (2020). However, advancements in research and technology in Artificial Intelligence (AI), expert systems and in Machine Learning (ML) are offering innovative solutions to address these challenges (Blessy, 2021; Tace *et al.*, 2023; Velmurugan *et al.*, 2024).

Ogidan *et al.* (2019), Ogidan *et al.* (2023) have done some proceeding research work in the irrigation analysis applying the use of FAO Penman-Monteith Equation and extending such to the smart irrigation systems. Smart irrigation systems based on AI and ML algorithms revolutionize water management in agriculture (Abioye *et al.*, 2022). Irrigated agriculture is one of the largest water users in arid and semiarid regions, according to Parmar *et al.* (2019) and Kunapara *et al.* (2016). In addition, the availability of valuable temperature estimate data via remote sensing and geographical information systems plays a significant role in agricultural production, (Parmar *et al.*, 2019). Irrigation with a timer is not the only feature of smart irrigation systems. To maximize and improve irrigation practices, agriculture, and other water-dependent businesses, smart irrigation systems are technologically sophisticated solutions (Talaviya *et al.*, 2020; Obaideen *et al.*, 2022; Vallejo-Gomez *et al.*, 2023). It makes use of intelligent and real-time data. It leverages real-time data and intelligent algorithms to optimize crop irrigation schedules and water delivery. Smart irrigation systems have been determined to ensure that crops receive the precise adequate amount of water precisely when and where it is needed by various factors, including soil moisture levels, weather forecasts, evapotranspiration rates and crop water needs (Obaideen *et al.*, 2022). These systems ensure that water is used more precisely and controlled, leading to benefits such as water conservation, sustainable crop production and reduced operational costs (Ali *et al.*, 2023); (Sharifnasab *et al.*, 2023). Predicting agricultural drought, which leads to substantial yield losses in major crops, is a more challenging than assessing meteorological and hydrological droughts. In order to improve water utilization in irrigation fields, several interconnected components make up the smart irrigation system. The typical IOT-based smart irrigation diagram is shown in Figure 1 below.

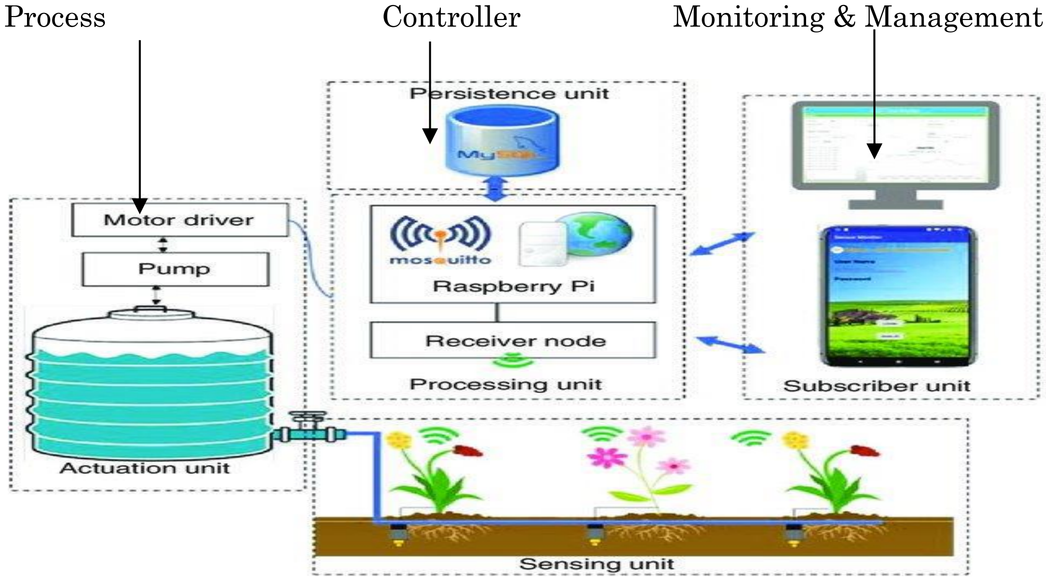

Figure 1. *IoT-Based Smart Irrigation System Diagram (Khriji et al., 2021).*

Knowledge-Based Algorithms

Knowledge-based algorithms are computer programs designed to imitate human experts' decision-making processes in a precisely defined field, such as irrigation management. These algorithms can effectively consider various variables and decision-making processes to maximize crop output and water utilization. In contrast to traditional process-based models, knowledge-based algorithms require less data and computation power, making them more practical and efficient for irrigation scheduling.

Applications of Knowledge-Based Algorithms in Irrigation Scheduling:

Expert systems are a common application of knowledge-based methods for irrigation scheduling. Expert systems in similar dimensions are computer programs that can simulate the decision-making processes of human specialists in a defined discipline, such as irrigation management. These systems typically consist of an information based (containing domain-specific data) rules, heuristics, and a reasoning process, known as the inference engine, that uses this information to make decisions.

The Decision Support System (DSS), developed by the Food and Agriculture Organization (FAO) of the United Nations, is an example of a knowledge-based irrigation scheduling algorithm. B on FAO Irrigation and Drainage Paper No. 56, this approach provides a comprehensive framework for determining agricultural water requirements and scheduling irrigation. The DSS uses an inference engine to evaluate input data (soil moisture and weather) and apply relevant rules and algorithms to determine the optimal irrigation plan.

Benefits of Knowledge-Based Algorithms

One of the primary benefits of knowledge-based algorithms in irrigation scheduling is that they require less data than complete models. Instead of needing many numbers of parameters that are often difficult to measure or estimate, knowledge-based algorithms only require a small number of parameters, which can be simpler and more readily available. This makes the approach more practical and feasible when data is scarce.

Another advantage is that knowledge-based algorithms are more efficient in computation than fully process-based models. This means that decisions can be made more quickly and with less computational power, making the approach more practical for on-farm implementation.

This research proposes using knowledge-based algorithms and reduced parametric estimations for irrigation scheduling. The proposed approach offers several benefits over traditional methods, including reduced data requirements, increased efficiency of computation, and practical applicability in scarce data scenario. The development and implementation of this method could significantly improve the decision-making process for irrigation scheduling, leading to improved water use efficiency and crop productivity.

LITERATURE REVIEW

Irrigation scheduling is a crucial aspect of agriculture, as it helps optimize water usage and ensure the efficient management of water resources. Knowledge-based algorithms have been widely explored in this domain, leveraging various techniques and approaches to enhance irrigation scheduling decisions. One prominent study by Karimi *et al.* (2021) presents a comprehensive review of knowledge-based algorithms for irrigation scheduling. The authors explore different forms of knowledge-based systems, including fuzzy logic, rule-based systems, and artificial neural networks. They highlight the potential of these algorithms in integrating various factors, such as soil moisture, weather conditions, crop characteristics, and historical data, to provide accurate and context-specific irrigation recommendations. Karimi *et al.* (2021) explores the use of knowledge-based algorithms for irrigation scheduling. It examines various strategies and techniques employed in recent years, highlighting the potential of these algorithms to improve water management in agriculture.

Key Findings

The review identifies several key findings, including

Knowledge-based algorithms can significantly improve irrigation efficiency and water productivity. These algorithms can integrate various data sources, such as soil moisture sensors, weather forecasts, and crop growth models. Different types of knowledge-based algorithms offer varying advantages and limitations, depending on the specific application (Hanyu Wei *et al.*, 2024).

Another study by Brouwer *et al.* (2018) and Gregory *et al.* (2024) focuses on the development of a knowledge-based decision support system in irrigation scheduling. They have proposed a system that combines real-time sensor data, weather forecasts, and expert knowledge to generate irrigation schedules designed to the specific needs of various crops and environments.

In a similar vein, a researcher presents a fuzzy logic-based irrigation scheduling algorithm that incorporates soil moisture, evapotranspiration, and crop water requirements to optimize water usage. Their approach demonstrates the effectiveness of knowledge-based techniques in adapting to variable environmental conditions and achieving water conservation goals, Adel *et al.* (2020). Furthermore, Lozano *et al.* (2020) explore the integration of the processes in machine learning such as support vector machines and artificial neural networks, with knowledge-based approaches for irrigation scheduling. Their findings suggest that the combination of data-driven and knowledge-based techniques can lead to more accurate as well as robust irrigation decisions.

These studies and others in the field have contributed to the growing body of knowledge on the application of knowledge-based algorithms in irrigation scheduling. By leveraging expert knowledge, sensor data, and advanced computational techniques, researchers have developed innovative solutions to address the challenges of efficiency concerns in agricultural water management activities.

Managing waste efficiently is critical to sustainable agriculture, especially in the geographical regions with the problems of water scarcity. Irrigation scheduling, the practice of determining the optimal timing and amount of water to apply to crops, is a key aspect of water management. Legacy irrigation scheduling methods most times rely on manual monitoring and expert judgment, which can be labor-intensive and subject to human error. In recent times, the application of artificial intelligence (AI) techniques has been defined as a promising approach to improve irrigation scheduling.

AI-based Irrigation Sheduling

Researchers have explored various AI methods for irrigation scheduling, including Predictive models: Machine learning models, such as Decision Trees and Artificial Neural Networks, have been used to predict crop water requirements based on factors like weather, soil conditions, and plant characteristics Darouich *et al.* (2017). Optimization algorithms: Optimization techniques, including genetic algorithms and reinforcement learning, have been employed to determine the optimal irrigation strategies which are capable of maximizing crop yield and at the same time minimizing quantity of water usage Deb (2020) and Shiri *et al.* (2017).

Sensor-Based Systems

Ayodele *et al.* (2021) has done a paper review on the application of sensor in an agricultural endeavor in his overview paper for sensor analysis for Health Monitoring, which is based an expert system design for catfish pond. The integration of AI with sensor networks, such as soil moisture sensors and remote sensing data, has enabled real-time monitoring, adaptive irrigation timing and scheduling Taghvaeian *et al.* (2014).

Benefits of Irrigation Scheduling based on AI.

The application of AI to irrigation scheduling has shown several potential benefits: Improved water use efficiency: AI-based models can optimize irrigation schedules reducing water consumption without compromising crop yields Deb *et al.* (2002).

Reduced labor and costs: Automated, AI-driven irrigation systems can reduce the need for manual monitoring and decision-making, thereby lowering labor and operational expenses (Hedley *et al.*, 2009).

Enhanced resilience to climate variability-based systems can adapt to changing environmental conditions, such as drought or excessive rainfall, and provide more accurate and responsive irrigation scheduling Taghvaeian *et al.* (2014).

Increased crop productivity: Optimized irrigation schedules can improve crop health and yield and enhance agricultural productivity (Deb *et al.*, 2002).

Some Applied Studies

Knowledge-based approaches to irrigation scheduling, on the other hand, are integrated with an emphasis on optimizing water use efficiency and maximizing crop yield, considering computational complexities in agro-hydrological systems. The key works have included learning-based and model predictive control frameworks, among which the study of multi-agent MPC for irrigation scheduling was performed by Agyeman *et al.* (2024) using k-means clustering with hydraulic parameter estimates. The system they came up with resulted in 7-23% water savings and increased Intrinsic Water-Use Efficiency (IWUE) by up to 35%, Agyeman *et al.* (2024). In the same direction, model reduction techniques combined with empirical farmer knowledge have made efficient scheduling possible at large hence keeping crops at a non-stressful state with water savings included in the process of Sahoo *et al.* (2022). This contrasts with IoT-based methods that focus on automating irrigation through real-time moisture monitoring, which simplifies operations but lacks the multi-variable optimization seen in Model Prediction Control (MPC) approaches, Jha *et al.* (2023). These methods underscore the importance of parametric simplifications, which are essential for managing large datasets, improving prediction accuracy, and enhancing computational efficiency. Advances in sensor integration, remote sensing, and machine learning further refine these systems to bridge conventional irrigation practices and sustainable water management. Each system brings out the dual goals of sustainability and productivity in tackling the challenges modern agriculture faces. Table 1 below shows insights to some major work in irrigation scheduling and as cited in column 1 of the table.

Table1. *Insights to some major work in irrigation scheduling.*
Source Analysis

No.	Source	Key Insight
1	Learning-based multi-agent MPC for irrigation scheduling (Agyeman *et al.*, 2024)	Demonstrates high efficiency in irrigation water use through advanced multi-agent MPC frameworks.
2	Knowledge-based optimal irrigation scheduling of three-dimensional agro-hydrological systems (Sahoo *et al.*, 2022)	Highlights optimization with reduced dimensionality and empirical knowledge integration.
3	IoT-based irrigation management system (*Jha et al*., 2023, Mallareddy *et al.*, 2023)	Explores automation in irrigation management using IoT for real-time monitoring.

Challenges and Limitations

While the application of AI to irrigation scheduling shows promise, there still exists several challenges and limitations that require to be addressed: Data availability with the quality: The performances of AI models are highly dependent on data availability and data quality, which can be limited in some agricultural settings.

Interpretability and trust: The complex nature of some AI models, such as deep neural networks, can make it difficult for farmers and stakeholders alike to understand and trust the decision-making process (Hedley *et al.* 2009).

Integration with legacy systems: The integration of AI-based irrigation scheduling with existing farm management systems and infrastructure can be challenging, Taghvaeian *et al.* (2014).

Scalability and deployment: Scaling up AI-based irrigation scheduling from small-scale experiments to large-scale commercial adoption can be a significant hurdle Darouich *et al.* (2017). The application of AI to irrigation scheduling has demonstrated the potential to enhance the water use performance index, labor and cost optimizations, and improve crop productivity. Addressing the challenges and limitations will be crucial for the widespread adoption of AI-based irrigation scheduling in sustainable agriculture.

Advantages of Knowledge-Based Algorithms

Interpretability and Transparency: Knowledge-based algorithms are often more interpretable and transparent than black-box machine learning models. The underlying knowledge base and decision-making process can be explicitly defined, making it easier for users to understand and trust the system's outputs Buchanan and Shortliffe (1984).

Reasoning and Inference: Knowledge-based algorithms can perform complex reasoning and inference based on the rules and relationships stored in the knowledge base. This allows them to handle tasks that require logical thinking, such as troubleshooting, diagnosis, and decision-making.

Domain-Specific Knowledge Incorporation: Knowledge-based algorithms can incorporate and leverage domain-specific knowledge, which can be particularly valuable in specialized or complex domains where expert knowledge is crucial for effective problem-solving Durkin (1994).

Adaptability and Flexibility: Knowledge-based algorithms can be more adaptable and flexible compared to data-driven algorithms, as the knowledge base can be easily updated or modified without retraining the entire system Giarratano and Riley (2005).

Explanation and Justification: Knowledge-based algorithms can provide explanations and justifications for their decisions, which is essential in applications where accountability and transparency are critical, such as in the medical or legal domains Buchanan and Shortliffe (1984).

Handling Uncertainty and Incomplete Information: Knowledge-based algorithms can often handle uncertainty and incomplete information more effectively than data-driven algorithms, by incorporating uncertainty handling mechanisms, such as fuzzy logic or Bayesian reasoning, into the knowledge base Durkin (1994).

Limitations and Challenges

While knowledge-based algorithms offer several advantages, they also face some limitations and challenges:

Knowledge Acquisition and Maintenance: The developing and maintaining a comprehensive knowledge base is often a time-consuming and labor-intensive process, always requiring the involvement of domain experts (Giarratano and Riley, 2005).

Scalability and Performance: Knowledge-based algorithms may not scale as well as data-driven algorithms, particularly for large-scale or high-volume applications, due to the computational overhead associated with reasoning and inference (Durkin, 1994).

Adaptability to New Domains: Transferring knowledge-based algorithms to new domains can be more challenging data-driven approaches, as the knowledge base may need to be significantly modified or rebuilt Buchanan and Shortliffe (1984). Knowledge-based algorithms offer unique advantages, such as interpretability, reasoning capabilities, and the ability to incorporate domain-specific knowledge. While they face some limitations, such as knowledge acquisition and scalability, they remain valuable in applications where transparency, accountability, and domain expertise are crucial. As AI evolves, the synergistic integration of knowledge-based and data-driven approaches can lead to more effective and robust problem-solving solutions.

Literature review on the tools used for the deployment of knowledge-based irrigation algorithms:

The deployment of knowledge-based irrigation algorithms, which rely on expert knowledge and rule-based reasoning to optimize irrigation scheduling, requires various tools and technologies. These tools play a significant role in correct implementation and integration of knowledge-based irrigation systems in agricultural practices.

Tools for Deploying Knowledge-Based Irrigation Algorithms

Expert Systems Shells and Toolkits

Expert system shells and toolkits, such as Jess (Java Expert System Shell), CLIPS (C Language Integrated Production System), and Drools, provide a framework for building and deploying knowledge-based systems. These tools typically include features for knowledge representation, inference engines, and user interfaces, making it easier to develop and deploy knowledge-based irrigation algorithms Giarratano and Riley (2005).

Geographic Information Systems (GIS)

Geographic Information Systems software, such as ArcGIS or QGIS, can be integrated with knowledge-based irrigation algorithms to incorporate spatial data and perform spatial analysis. This allows for integrating factors like soil properties, topography, and microclimate conditions into the decision-making process Shrestha *et al.* (2020).

Sensor Networks and IoT Platforms

Deploying knowledge-based irrigation algorithms often relies on sensor networks and Internet of Things (IoT) platforms to collect real-time data on plant growth, soil moisture and weather conditions. These sensor data can be used to update the knowledge base and adapt the irrigation schedule accordingly Taghvaeian *et al.* (2014).

Decision Support Systems (DSS)

Knowledge-based irrigation algorithms can be integrated into decision support systems (DSS), provide a user-friendly interface for farmers and irrigation managers to access, interpret, and act upon the recommended irrigation schedules. These DSSs often incorporate visualization tools, optimization algorithms, and economic models to support decision-making Darouich *et al.* (2017).

Cloud computing and Web-based Platforms

Cloud computing platforms and web-based applications can facilitate the deployment of knowledge-based irrigation algorithms by providing scalable computing resources, secure data storage, and remote accessibility. This allows for centralized management and distribution of the knowledge-based system to multiple users or locations.

Mobile Applications and Smartphones

Mobile applications and smartphones can serve as an interface for knowledge-based irrigation algorithms, allowing farmers to access and interact with the system directly in the field. These mobile tools can provide real-time recommendations, enable data input, and facilitate communication with the knowledge base Hedley *et al.* (2009).

Challenges and Considerations

Deploying knowledge-based irrigation algorithms requires addressing several challenges and considerations which are explained as follows:

Integration with Existing Farm Infrastructure

Seamless integration of the knowledge-based system with existing farm management systems, irrigation equipment, and data sources is crucial for successful deployment Taghvaeian *et al.* (2014).

User Acceptance and Training

Ensuring user acceptance and providing adequate training for farmers and irrigation managers is essential for successfully adopting knowledge-based irrigation algorithms (Hedley *et al.*, 2009).

Data Quality and Availability

The performance of knowledge-based irrigation algorithms is predominantly dependent on the quality of data; and availability of the input data, requiring careful consideration of sensor calibration, data management, and quality control.

Scalability and Maintenance.

Scaling up the deployment of knowledge-based irrigation algorithms from small-scale pilots to large-scale commercial applications, and maintaining and updating the knowledge base over time, can pose significant challenges Darouich *et al.* (2017). The deployment of knowledge-based irrigation algorithms relies on various tools and technologies, including expert system shells, GIS, sensor networks, decision support systems, cloud computing, and mobile applications. By leveraging these tools, knowledge-based irrigation algorithms can be effectively integrated into agricultural practices, which leads to improved water management and sustainable irrigation implementations. However, addressing the challenges related to integration, user acceptance, data quality, and scalability are necessary for these knowledge-based systems' successful deployment and long-term success.

Use of knowledge-based algorithms for reduced parameter irrigation scheduling:

Irrigation scheduling is a critical aspect of water management for some agricultural processes, as it aims to optimize the timing and amount of water application for maximizing crop yield and minimizing water usage. Traditional irrigation scheduling methods often rely on complex models that require many input parameters, such as soil properties, weather data, and crop characteristics. This can make implementing and adopting these methods challenging, particularly for small-scale farmers with limited resources. Knowledge-based algorithms have been to be a promising approach to addressing this issue by reducing the number of required parameters while still maintaining the effectiveness of irrigation scheduling.

In Knowledge-Based Algorithms for Reduced Parameter Irrigation Scheduling, there are the adoptions of

Rule-based Irrigation Scheduling (RBIS): RBIS rely on a set of expert-derived rules and heuristics to determine the optimal irrigation schedule and amount. These rules can be based on readily available parameters, such as soil moisture, evapotranspiration rates, and crop growth stage, reducing the need for detailed soil and weather data Guo *et al.* (2021), while the Case-Based Reasoning (CBR) scenario could be analyzed with five steps, represented as follows: represent, retrieve, reuse, revise, and retain as shown in figure 2 below, called the R5 CRB model.

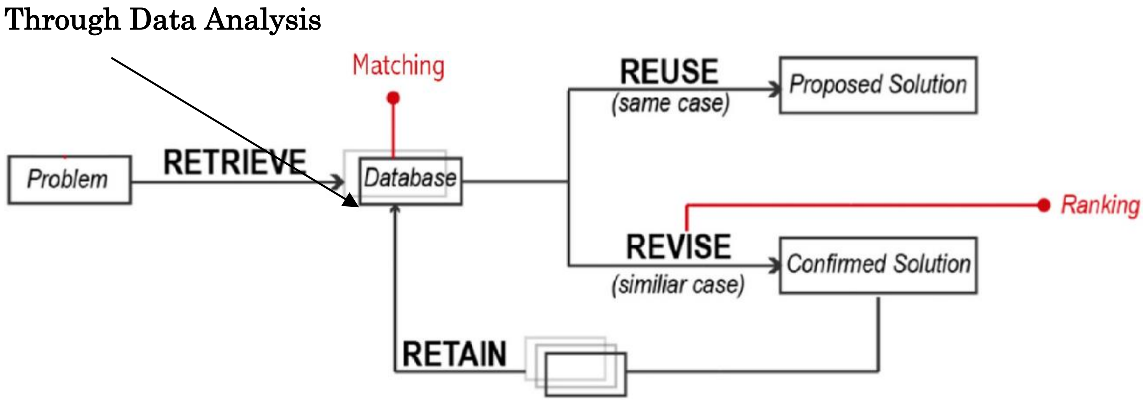

Figure 2. *Diagram For The R-5 model of the CBR approach,* Li *et al.* (2023).

Fuzzy Logic Irrigation Scheduling: Fuzzy logic-based irrigation scheduling algorithms can incorporate expert knowledge and linguistic rules to make irrigation decisions. Using fuzzy membership functions and inference rules, these algorithms can handle imprecise or uncertain data, such as soil moisture levels or weather forecasts, without requiring precise numerical inputs (Benzaouia *et al.*, 2023).

Adaptive Neuro-Fuzzy Inference Systems (ANFIS): The ANFIS integrates the advantages of fuzzy logic and artificial neural networks to create a hybrid knowledge-based algorithm. ANFIS can learn from available data to fine-tune the fuzzy rules and membership functions while allowing expert knowledge integration. This approach can reduce the required parameters compared to traditional irrigation scheduling models (Rouhani *et al.*, 2012).

Case-Based Reasoning (CBR)-based irrigation scheduling systems store and retrieve past successful irrigation strategies as cases, which can then be adapted to the current situation. This approach allows for the incorporation of expert knowledge system and experience without the requirement for a comprehensive numerical model, Zhaoyu *et al.* (2020).

Hybrid Approaches: Researchers have explored integrating knowledge-based algorithms with other techniques, such as sensor-based monitoring and optimization methods, to reduce the parameter requirements further while maintaining the effectiveness of the irrigation scheduling. For example, combining rule-based systems with soil moisture sensors or integrating fuzzy logic with genetic algorithms can lead to more efficient and adaptive irrigation scheduling Darouich *et al.* (2017); Shiri *et al.* (2017).

Benefits and Challenges

The use of knowledge-based algorithms for reduced parameter irrigation scheduling offers several potential benefits:

Reduced data requirements: By relying on smaller input parameters, knowledge-based algorithms can be more accessible and easier to implement, especially for small-scale farmers.

Improved decision-making: The incorporation of expert knowledge and reasoning can lead to more informed and context-specific irrigation decisions.

Adaptability and flexibility: Knowledge-based algorithms can be more easily updated and adapted to changing conditions than complex numerical models.

However, there are also challenges associated with the deployment of knowledge-based irrigation scheduling algorithms:

Knowledge acquisition and representation: Capturing and formalizing expert knowledge into a usable knowledge base can be a time-consuming and labor-intensive.

Validation and testing: Ensuring the accuracy and reliability of knowledge-based algorithms in real-world agricultural settings can be challenging.

Integration with existing systems: Seamless integration of knowledge-based irrigation scheduling with other farm management tools and infrastructure is crucial for widespread adoption.

CONCLUSION

The use of knowledge-based algorithms for reduced parameter irrigation scheduling shows promises in addressing the challenges of traditional irrigation scheduling models, particularly in terms of data requirements and accessibility. By leveraging expert knowledge, fuzzy logic, and adaptive learning, these algorithms can provide effective irrigation scheduling solutions while reducing the burden on farmers and irrigation managers. As the field continues to evolve, addressing the challenges related to knowledge representation, validation, and integration will be crucial for successfully deploying and adopting of knowledge-based irrigation scheduling in sustainable agriculture.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no conflict of interest.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

The authors declared that the following contributions are correct.

Abayomi AYODELE: Investigation, Methodology, Conceptualization, Data curation, Validation, Writing–original draft, Review, and Editing, Visualization.
Olugbenga OGIDAN: Investigation, Methodology, Conceptualization, Data curation, Validation, Writing–original draft, Review, and Editing, Visualization.
Adeseko AYENI: Investigation, Methodology, Data curation, Validation, Writing –original draft, Review, and Editing, Visualization.

ETHICS COMMITTEE DECISION

This article does not require any Ethical Committee Decision.

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