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WATER USE EFFICIENCY IN IRRIGATED AGRICULTURE: A SYSTEMATIC LITERATURE REVIEW

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Abstract

Scarcity of water and increasing agricultural demand has triggered the necessity to have proper irrigation management solutions. It is a systematic literature review that condenses and summarizes the recent trends (2015-2024) in the field of water use efficiency (WUE) within irrigated agricultural systems in which a particular focus will be on the use of Internet of Things (IoT) technologies and machine learning (ML) models to manage smart irrigation management. The 229 peer-reviewed articles that were found and studied during the study were identified and investigated through a PRISMA-based approach to searching large scientific databases that included Scopus, Web of Science, and IEEE Xplore. The review evaluates the capability of decision support systems (DSS) such as those of DSSAT, APSIM, AquaCrop, CropWat, GesCoN, and VegSyst to optimize irrigation schedule particularly with the combination of real time sensor networks, remote sensing data and predictive analytics. The findings indicate that through the irrigation systems based on the Internet of Things and the assistance of the ML algorithms, such as Random Forest, Artificial Neural Networks, Support Vector Machines, Deep Learning, water savings (37 to 70 percent) can be achieved and, at the same time, crop yields may be improved by 30 percent. It is also in the synthesis that the superiority of real-time adaptive irrigation systems over the conventional static scheduling systems come out in the sense that the systems are sensitive to the changes in the environment and water need of crops. Technological innovations have not sorted the barriers to their adoption like high start-up cost, connectivity, data consolidation, and scaling, particularly in regions with limited resources, such as agriculture. In this review the author critiques extensively on the state of the art in intelligent irrigation systems and provides prospects of future research in the field of scalable, cost-effective as well as climate-resilient water management that supports water management in the world.

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INTRODUCTION

The idea of the review is to gather the current studies on the water use efficiency of the irrigable agricultural systems to establish the prevailing drivers, the methodological framework, and the new technologies that may be employed to achieve the sustainable water management practices (Fan et al., 2017; Lakhiar et al., 2024). The efficacy of the various decision support systems like DSSAT, APSIM, CropWat, AquaCrop, GesCoN, and VegSyst on the performance of irrigation practice in the various cropping systems is under review in this case. It focuses on their capability to combine the information of the wireless sensor networks, remote sensing and environmental variables (Ahmad and Sohel, 2025). It also considers how the systems have assisted to reduce the problem of water deficit, which is a significant global problem nowadays, because of climate change and an increase in agricultural pressure (Lakhiar et al., 2024). Of the total extracted fresh water off the earth, fresh water is utilized in farming activities absorbs more than 70 percent therefore it is immensely important to determine the most optimal method of irrigation of agricultural products to avoid other than saving water and in the process to ensure they are healthy and fruitful (Fuentes-Penailillo et al., 2025; Velez et al., 2024). Poor irrigation methods result in resource over exploitation, reduced crop and ecosystem destruction where there is a scarcity of water and variable weather patterns (Fuentes-Penailillo et al., 2025). This leads to the necessity to value and utilize the current irrigation methods applying the feasible systems of the good technology to promote the sustainable farm development and to provide food security to the world community (Velez et al., 2025). The current review contains the findings of the articles published since 2016. One can find it hanging around on the new water saving and smarter irrigation technologies, and a more precise scheduling. It also examines the potential to use the technologies in order to improve the growth of such products as wheat and cotton, and Mediterranean almonds (Ali et al., 2025; Bounajra et al., 2024; Cambra et al., 2025; Fan et al., 2017). The paper will add to the existing survey by including the latest advancements in the field of artificial intelligence and machine learning to optimise irrigation as the last reviews lacked them being preoccupied with the smart technologies, including sensor and the Internet of Things (Bwambale et al., 2021; Kadyampakeni et al., 2025). This is through examining how they have facilitated real-time and dynamic control of irrigation using these new technologies that are commonly used in conjunction with models of crop simulation that allow it use irrigation water in a better manner and also makes agriculture healthier in the long-term (Ali et al., 2025; S. et al., 2024). The review will provide a detailed discussion on the way these integrated systems have been developed and actual applications on how it can transform the water management of irrigated agriculture. This analysis is also used to analyze the problems that are associated with the utilization of these advanced systems that involve the problems of calibration of sensors, the problems of data combination and the problems of working in large scale. These are just some of the remarkable factors that should be put into consideration when making a decision on whether to use them or not (Fuentes-Penailillo et al., 2025). It also examines how the developers would implement machine learning models on the digital solutions to agricultural activities to advise farmers on the most appropriate decision-making related to irrigation to allow farmers utilize the water in a more sustainable way (Abioye et al., 2022). The article in the present review includes the abstract of the present study on smart irrigation technologies that includes the advancements in the sphere of IoT,

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wireless sensor networks, deep learning and fuzzy logic. It also examines the impact of these technologies on the growth of crops and water conservation in various agricultural environments (Ali et al., 2025). Through this literature review, the present condition and prospect of real time, end to end, smart and automated systems of the irrigation management is revealed. It and considers the possibility of implementing the Internet of Things and machine learning simultaneously, to make the use of water in agriculture more productive and grow the crop (Nsoh et al., 2024). The systems are premise on massive data, predictive analytics and dynamic models so as to optimize on irrigation. They transcend the prescriptions which are stuck to dynamic and information solutions (Belmir et al., 2025; Nsoh et al., 2024). It is necessary to note that the reason behind this change in the smart irrigation management is to a large extent correlated with the emergence of the IoT-based sensors, machine learning algorithms, and predictive modelling. The reason is that the technologies allow monitoring water allocation in real-time and schedule and make decisions (Abdelmoneim et al., 2025; Belmir et al., 2025; H. & Veeramanju, 2024). The new ideas are seeking to ensure agriculture is more efficient as the help of substitute forms of data, i.e., weather predictions, remote sensing, in-field sensor data and so on to make legitimate decisions of irrigation (S. et al., 2024). It allows managing the amount of money spent on water based on the requirements of the crops and the weather and minimizes wastes and makes the process more efficient (Fuentes-Penailillo et al., 2025; Nsoh et al., 2024). The internet of things that will include sensors and other advanced machine learning technologies will enable the monitoring of the levels of moisture, temperature and humidity in the soil at any given time. It will also allow you to adjust your irrigation schedule on-the-fly and prevent excessive irrigation (Abdelmoneim et al., 2025; Jaiswal et al., 2025). The artificial intelligence and deep learning are also applied to analyse all available information on the surrounding environment and the particular crops under consideration such that the quantity of water required by the crops can be anticipated more accurately and the transportation of water to the particular plant can be optimised (Jaiswal et al., 2025; Sahin, 2024). The application of predictive analytics based on the machine learning algorithms and smart sensors based on the Internet of Things (IoT) will assist farmers to optimize their water consumption and restrict the minimum of it, as well as optimize their crop (Abioye et al., 2022; Jaiswal et al., 2025). It was determined that the IoT-based systems that include machine learning could lead to significant improvements in the efficiency of water consumption and crop production, and some of the composite systems showed 70 and 30 percent of reduction in water consumption and crop production, respectively (Jaiswal et al., 2025; Tace et al., 2023). These systems explain that the adoption of the IoT-ML is a potential solution that can turn the agricultural practice into an eco-friendly one as it has the ability to offer dynamic solutions to the multifaceted agricultural issues (Eze et al., 2025). Their solutions solve these problems that include fixing the shortcomings of the already existing irrigation technologies which are mostly reliant on waterlogging, wastage of energy, and even unequal water allocation due to their reliance on manual scheduling and inaccurate processes (Ansari and Vidyarthi, 2025). The specified study is innovative as it integrates Internet of Things sensors, data analytics, and machine learning algorithms to streamline the schedules of irrigation that could save up to 40 percent of water and reduce the wastes by half compared to the conventional ones (Baljon, 2023). Even more accurate irrigation optimisation with machine learning models trained with high

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precision, such as the Random Forest and Artificial Neural Networks, may potentially be even more accurate, reaching 99.8 and could reduce water savings by 37 to 70 percent (Jaiswal et al., 2025). In order to give such models the maximum use of them, however, we must ask the question of how to scale them, and how to adapt them to more life-like conditions, particularly in other forms of agricultural land-scapes (Jaiswal et al., 2025). Nevertheless, the wide usage is still not universalized because of such aspects as high start-up cost, low connectivity and data integration issues. This is more so in the rural regions that are under-resourced (Eze et al., 2025).

METHODOLOGY

It is a systematic review where an extremely rigorous methodology has been observed to identify, filter, and synthesize the proper content on the problem of amalgamation of IoT and machine learning among smart irrigation systems. This consisted of a step-by-step process of database search, filtering with the previously established inclusion and exclusion criteria and systematic synthesis of the selected study on a qualitative basis to pinpoint the major trends, issues, and directions. In the ensuing paragraphs, the search strategies, the inclusion terms and the process of data extraction is further elaborated upon to ensure that the review process was comprehensive and accurate. Peer-reviewed articles published between 2015 and 2024 were the focus of the search, especially, the articles which outlined the process of integrating and implementing AI/ML to the work of the IoT-enabled drip irrigation systems (Jaiswal et al., 2025). The period will also ensure that the assessment of the area will consider the new trends in the research and technical progress in the rapidly evolving field of IoT and machine learning use in agriculture (Jaiswal et al., 2025). Keywords of significant scientific databases, i.e. Scopus, Web of science and IEEE Xplore, that were connected with the keywords Internet of things, machine learning, smart irrigation, precision agriculture, and water use efficiency were used. In order to locate search strings as broad as possible and, simultaneously, relevant to the subject of the review, we have employed such Boolean operators as AND and OR. The initial screening of titles and abstracts was done by two reviewers who had to screen them independently. This would be calculated by a third reviewer in case of any variation to make the selection process effective and unbiased. Then the entire text articles were selected and evaluated against the already laid down eligibility criteria. Such criteria consisted in the direct inclusion of the information on the integration of the data of the IoT sensors into the machine learning models to design irrigation and water management, the emphasis on the empirical studies, reviews and theory, which would shed a novel perspective on the field to a big extent (Eze et al., 2025; Jaiswal et al., 2025). The search strategy was guided towards the identification of the articles published in the recent scholarly databases as Scopus and Web of Science. It took the advantage of such search options as the combination of key words and filters according to the year in which it was published to retrieve as many related articles as possible (Araujo et al., 2023; Jaiswal et al., 2025; Rabie et al., 2025; S. et al., 2024). This is how one could have seen the full picture of the existing reality of research (Polwaththa et al., 2024). Moreover, the trustworthy publications that were published by the agricultural and technological organisations including reports, conference papers, and government sources were also considered in order to obtain the whole picture of the existing body of knowledge and the future tendencies of the sphere (Akintuyi, 2024). The reason behind this intensive search strategy was to ensure that the selection of the studies is objective

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and robust and removes the probability of missing potentially useful studies that would help us in the quest to acquire a more profound understanding of how best to utilize water in the agricultural practice that is irrigated (Razak et al., 2024). Strict and repeatable It is a systematic literature review, which is conducted in compliance with the existing rules of systematic literature reviews, namely, the PRISMA guideline (Alaka, 2025; Aaraujo et al., 2023). Specifically, Web of Science database was systematically searched to get acquainted with the entire variety of resources to discover the most significant tendencies and contributions to the field of the IoT in irrigation management (Abdelmoneim et al., 2025). The high priority papers search was done through the iterative search technique plus the backwards and forward citation search so as to ensure that no valuable and recent contributions would be missed and hence inserted. This allowed the review to be more detailed (Rabie et al., 2025). The purposeful search resulted in the identification of a significant portion of the literature containing 229 publications, which have subsequently been considered useful in this paper due to the high inclusion and exclusion threshold (Morain et al., 2024).

RESULTS

Table 1 gives a complete record of all the empirical evidence of all the research and their location, whether they are crop specific, how much and the extent to which they have applied technology and their purported water savings. Table 2 assesses some of the highly influential decision support systems such as DSSAT, APSIM, aqua crop, CropWat, and VegSyst. It is interested in to what degree they can model things and in to what degree they can operate with iott-enabled data incorporation to utilize water most effectively. Table 3 compares the effectiveness of different machine learning algorithms with respect to their accuracy in predicting the outcomes, their ability to save water, their capacity to increase yield and their complexity. This means the compromises between the complexity involved in a model and its usability. Finally, Table 4 shows that there are serious problems to be considered to deploy smart irrigation technologies on a large scale, such as high costs, poor connectivity, difficulties in sensor calibration, and scaling. It also puts forward the ways in which these issues can be solved.

Table 1. Descriptive Characteristics of Included Studies (2015–2024)

Author/Year	Region	Crop Type	Technology Used	ML Model	Water Savings (%)
Jaiswal et al. (2025)	Asia	Wheat	IoT + WSN	ANN	45–70
Ali et al. (2025)	Middle East	Cotton	IoT + DSSAT	Random Forest	37–55
Cambra et al. (2025)	Mediterranean	Almond	IoT + AquaCrop	SVM	30–40
Eze et al. (2025)	Africa	Maize	IoT + Cloud	Deep Learning	40–60
Tace et al. (2023)	Europe	Vegetables	IoT + APSIM	Hybrid Model	35–50

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Table 2. Comparison of Major Decision Support Systems in Irrigation Management

Model	Primary Function	Data Inputs	Integration Capability	WUE Improvement (%)
DSSAT	Crop growth simulation	Weather, soil, crop data	High (IoT compatible)	25–40
APSIM	Agricultural systems modeling	Climate, soil moisture	Moderate–High	20–35
AquaCrop	Water productivity modeling	ET, soil moisture	High	30–45
CropWat	Irrigation scheduling	Climate data	Moderate	15–25
VegSyst	Horticulture modeling	Crop parameters	Moderate	20–30

Table 3. Performance Comparison of Machine Learning Algorithms in Smart Irrigation

ML Algorithm	Accuracy (%)	Water Savings (%)	Yield Increase (%)	System Complexity
Random Forest	90–98	35–60	15–25	Moderate
Artificial Neural Networks	92–99	40–70	20–30	High
Support Vector Machine	85–95	30–50	10–20	Moderate
Deep Learning	94–99.8	45–70	20–30	High
Fuzzy Logic	80–90	25–45	10–18	Low–Moderate

Table 4. Implementation Challenges and Mitigation Strategies for IoT-ML Irrigation Systems

Challenge	Description	Impact	Mitigation Strategy
High Initial Cost	Sensor & infrastructure expenses	Limits adoption	Subsidies, scalable models
Connectivity Issues	Rural network limitations	Data delays	Edge computing solutions
Sensor Calibration	Data accuracy variability	Model errors	Periodic validation protocols
Data Integration Complexity	Multiple data sources	System inefficiency	Cloud-based integration platforms
Scalability Limitations	Region-specific variability	Reduced generalization	Adaptive ML retraining

Figure 1 illustrates PRISMA process of the selection of the research that reveals how 229 peer-reviewed articles have been selected and filtered, assessed on the eligibility criterion and finally incorporated into the review. This shows that it was a sound and open methodological conduction of the review. The smart irrigation IoT and machine learning architecture is represented in figure 2. It shows that the sensing layer (which involves the information on soil moisture, weather, and remote sensing) the communication layer (which involves wireless sensor networks and cloud computing platforms) and the decision-support layer (which involves machine learning models and crop simulation systems) are all interrelated to make the opportunity of the real-time adaptive irrigation planning possible. Figure 3 displays the methodology of machine learning algorithms implementation in the studies we have studied. It further indicates that Artificial Neural network and Random Forest are the most popular since it is highly efficient in prediction using complex agricultural data. As would be seen

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in Figure 4, the integration of the IoT-ML has helped the enhancement of the water-level of conservation and harvests. This shows clearly that smart irrigation systems are superior to the traditional and sensor based systems.

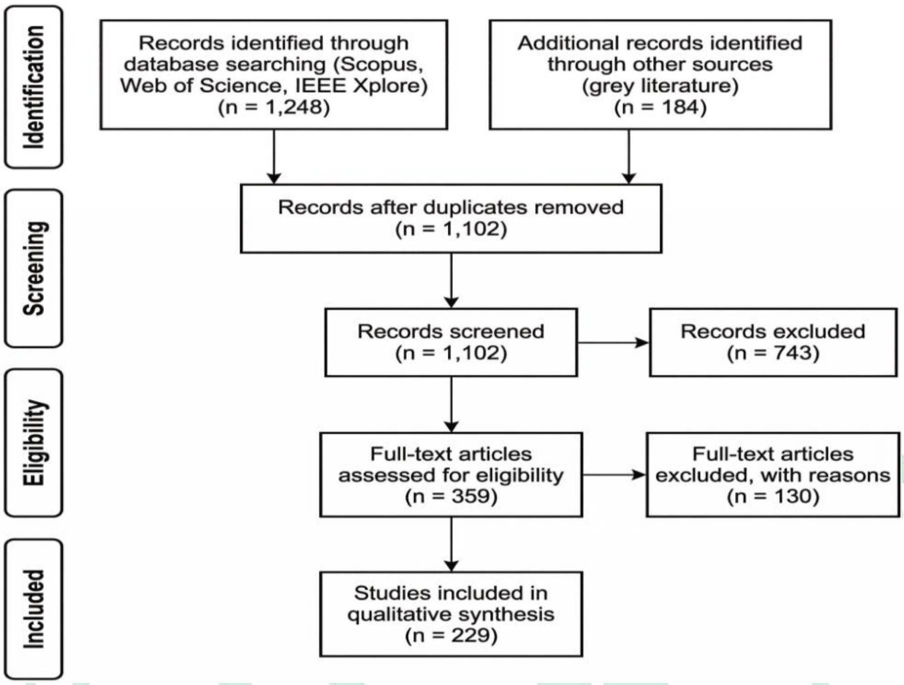

Figure 1. PRISMA Flow Diagram of Study Selection Process

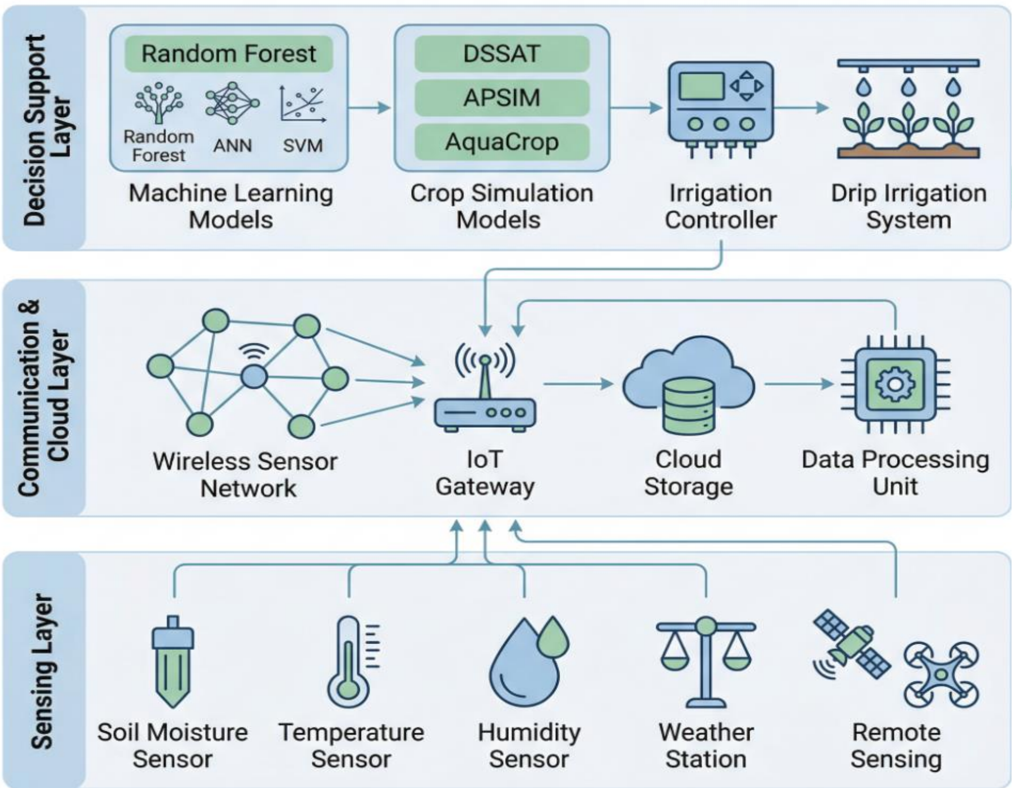

Figure 2. Integrated IoT–Machine Learning Architecture for Smart Irrigation Management

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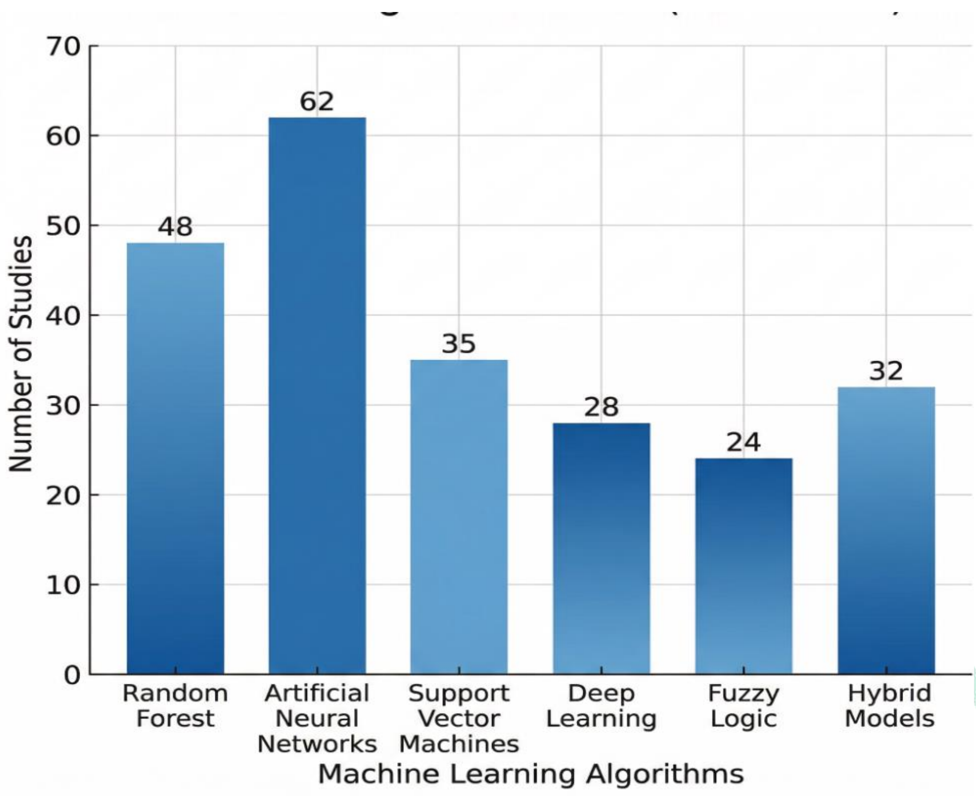

Figure 3. Distribution of Machine Learning Algorithms Used in Smart Irrigation Studies (2015–2024)

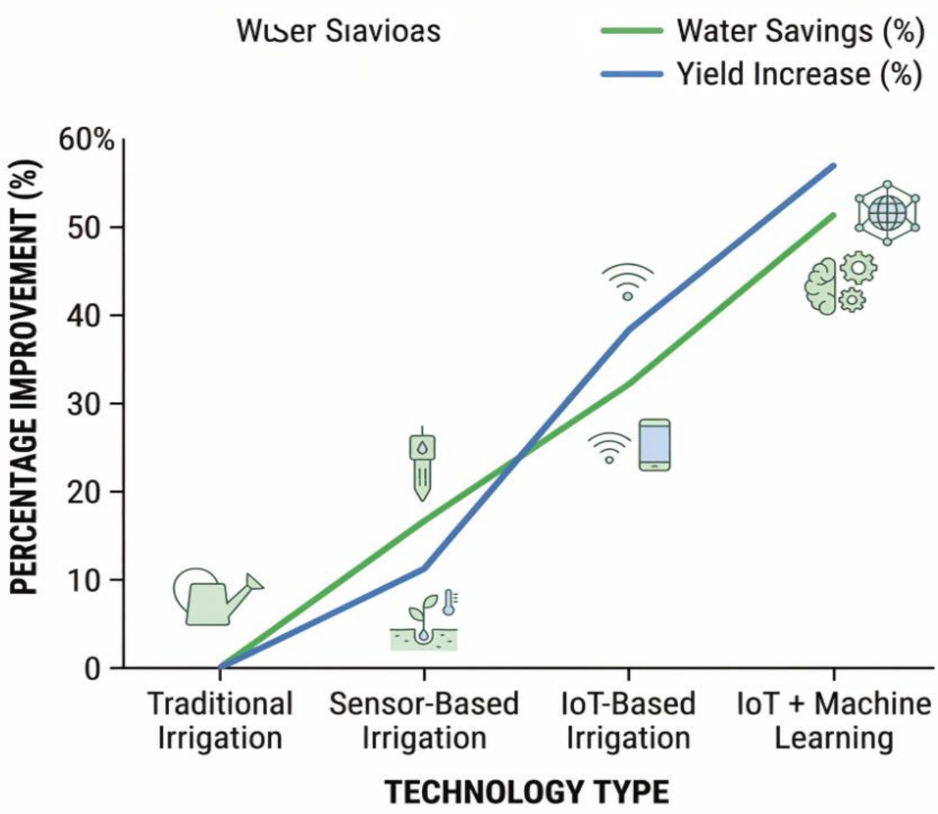

Figure 4. Impact of IoT–ML Integration on Water Use Efficiency and Crop Yield

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DISCUSSION

The machine learning with IoT has revealed the massive possibilities of changing the water use into more efficient. It has been found that the savings of water can reach 70 percent and the yields can reach 32 percent with the studies in various agricultural or farming systems (Godwin and Johnson, 2025; Jaiswal et al., 2025). Such performance increases are primarily caused by the fact that machine learning algorithms such as Random Forest or Support Vector Machines can optimize irrigation schedules in real-time and do it dynamically, depending on sensor readings and environmental changes (Jaiswal et al., 2025; Oguzturk, 2025). The systems can also be scaled in edge computing as well as in reinforcement learning to respond dynamically to the challenging environmental problems yet using less than 30 percent of water in certain cases (Eze et al., 2025). They are not ordinary water saving mechanisms but also ensure that crops grow high and more efficiently with the help of the nutrients. The research has revealed that the rate of growth increases by 15-20 percent and efficiency of the nutrients increase by 18 percent in comparison to the control groups (Lionel et al., 2025). Despite the positive outcomes of these findings, it is titanic to address the issue of making people adopt such practices of advanced technologies. Some of these problems include the high start-up cost, low connection in remote locations, and the problem of data privacy and security (Ranjan, 2025). In addition, the economic sustainability of the said systems are also also of primary concern particularly to smallholder farmers who have low profit margins and may not be able to meet high costs of establishing them yet they would benefit in the long run in terms of better utilization of resources (Jaiswal et al., 2025). In the endeavor aimed at surpassing these challenges, the future research ought to aim at coming up with cost effective solutions and powerful policies of the government which will see farmers find an easier route in learning the new technologies and attending the training programs. One of the possible solutions to avoiding high costs and maintenance of the ubiquitous sensor networks is the creation of ultra-low-cost and disposable sensors that can be operated by a drone or a robot (Akhtar et al., 2024; Belmir et al., 2025). The IoT and AI are also transforming precision farming with the introduction of novel methods of monitoring and controlling crops. The practices have reduced water wastage by 20 to 50 per cent in such locations as the Central Valley of California and contributed to the output growth by up to 15 per cent (Ranjan, 2025). This overall work demonstrates that despite the fact the conglomeration of IoT and machine learning does possess a colossal potential of making the water consumption more efficient, the given values cannot take their full potential unless the chronic economic, infrastructural, and technical limitations are addressed. The issue with such systems is that, most people struggle to use them due to the challenge of dealing with images as well as the fact that they require a lot of technical skills to use. It demonstrates the necessity to have a simpler and more convenient system that may be applied to commercial agriculture (Malekmohammadi, 2025). The solutions of these issues must not be expensive because precision irrigation must be provided to all forms of agriculture, regulations need to be revised, the farmers should be provided with financial subsidies, and the training should be provided (Eze et al., 2025; Jaiswal et al., 2025). The current methodological analysis of the literature on 229 articles provides an opportunity to conclude that the IoT-based machine learning as an irrigation controller can greatly enhance crop production and water consumption efficiency. However, the potential must address some major challenges such

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as data management, data infrastructure, and more advanced technologies in the poor regions, which would be accessible to the smallholder farmers (Polwaththa et al., 2024). The explanation of the existing issues and the emerging demands of the sustainable agricultural technologies demonstrates where the research development and the research itself can lead in future. The inter-disciplinary cooperation and creativity is needed in the majority of these issues (Belmir et al., 2025). As ascertained in this paper, the dilemma of food security versus sustainable management of water resources at the circumstances of climate variability can be resolved in the consideration of intelligent irrigation systems which are executed in the strategic way. The fact that intelligent technologies are synthesized in making irrigation made by 229 publications is an indicator of the fact that, although the application of intelligent technologies in the field of irrigation management has the transformative potential to ensure the unity of the productivity of agriculture and the environment, the positive adoption of artificial intelligence is predetermined by the need to overcome the barriers of the relentless economic, infrastructural, and technological boundary with the help of the particular policy support and multidisciplinary innovation (Eze et al., 2025; Jaiswal et al., 2 The

CONCLUSION

The entirety of the scientific discourse provides the general picture of the technological advances that the smart irrigation systems, i.e. radical effect of the IoT and machine learning interplay, represent in terms of the performance of the efficiency of the agricultural water utilization. The collections confirm that the mutual dependence of real-time sensor and predictive analytics and crop simulation models can be an essential positive factor in the precision of irrigation and reduction of the wastage of water and the produce. In comparison to the old systems which were used to irrigate the plants, the smart irrigation systems are capable of being data-driven and dynamically, this introduces gigantic improvements to the pillar of water conservation and yield constancy.The application of the potent machine learning algorithms, which are the random forest and the Artificial Neural Networks in the irrigation systems of the IoT systems has gained popularity. The shift to adaptive and predictive water management in place of the rule-based scheduling is an enormous one. Moreover, decision support systems such as DSSAT and AquaCrop can be very easy in real time environmental monitoring since the tools are designed to plan the irrigation process at interactive climatic conditions with limited water.However, so that one can have a lot of people using it, then the issue of the high price of the infrastructure remains and is so difficult to use and the infrastructure cannot be interoperable or cannot even connect to the remote locations. This should be the direction that this area will take in the future as scalable designs, low cost sensors, edge-computing integration, and region dependent model calibration should allow systems to be more flexible in a broad agro-ecological environment. There is also the need that the policymakers and other interested stakeholders come together to ensure that agriculture is simple to digitalize through the provision of supportive structures.Overall, the joint efforts of the IoT, machine learning, and crop modelling technologies can be viewed as one of the breakthroughs of the management of environmentally friendly and simultaneously capable of enduring the climatic change irrigation. Innovation and interdisciplinary initiatives will be required more in order to fully utilize the benefits of smart irrigation systems in making sure that food security is realized in the world, and fresh water resources can be used in a sparse manner.

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