AI-DRIVEN IRRIGATION: THE PATH TOWARDS SMART IRRIGATION SYSTEMS TO ENSURE AGRICULTURAL SUSTAINABILITY

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RESEARCH ARTICLE

Abstract
Climate change and water scarcity have become critical challenges for global agriculture, significantly impacting crop productivity and irrigation efficiency. Romania has experienced intensified drought conditions, erratic rainfall patterns, and increasing desertification risks, necessitating the adoption of innovative water management strategies. Traditional irrigation methods, including flood irrigation and manual sprinkler systems, are inefficient, leading to excessive water consumption, evaporation losses, and soil degradation. These limitations highlight the urgent need for advanced, adaptive irrigation technologies. This study presents a comprehensive research article of AI-driven irrigation systems, focusing on their potential to enhance water-use efficiency and agricultural resilience in Romania. Artificial Intelligence (AI), combined with the Internet of Things (IoT) and machine learning algorithms, enables precise real-time monitoring of soil moisture, weather forecasts, and evapotranspiration rates. By leveraging predictive models and automated decision-making, AI-based irrigation minimizes water waste while optimizing crop hydration. A systematic analysis of international case studies demonstrates the effectiveness of AI-driven irrigation in reducing water usage by up to 50% while increasing crop yields by 15–25%. Furthermore, neural network-based irrigation scheduling systems and reinforcement learning models have shown significant improvements in water conservation and cost efficiency. European initiatives, including the Green Deal and Horizon Europe, provide financial and technological support to facilitate Romania's transition to smart irrigation. The findings underscore AI-driven irrigation as a crucial solution for sustainable water management, offering economic, environmental, and agricultural benefits. Future advancements in AI and IoT will further refine precision irrigation, ensuring long-term food security amid changing climate conditions.

Keywords: Artificial intelligence, smart irrigation, IoT, predictive algorithms, precision agriculture.
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INTRODUCTION

Water scarcity and climate change threaten agricultural productivity globally, highlighting the need for efficient and sustainable water management. Agriculture is particularly vulnerable in areas experiencing recurrent droughts and inconsistent rainfall. In Romania, recent climate trends have intensified water scarcity, with prolonged droughts increasingly impacting agricultural output and local communities.

Traditional irrigation methods predominantly utilized in Romanian agriculture—such as flood irrigation, manual irrigation scheduling, and basic sprinkler systems—often result in excessive water consumption, inefficiencies, and uneven water distribution. These conventional practices not only compromise water sustainability but also limit the economic viability of agricultural operations, leading to reduced crop yields and increased production costs.

In response to these challenges, Artificial Intelligence (AI) has emerged as a transformative approach capable of optimizing water use through smart irrigation systems. These advanced systems integrate technologies such as Internet of Things (IoT) sensors, machine learning algorithms, predictive analytics, and automated decision-making processes. AI-driven irrigation technologies enable precise monitoring of soil moisture levels, weather forecasts, crop conditions, and evapotranspiration rates, facilitating real-time adjustments in water distribution.

In Romania, the urgency of adopting innovative solutions like AI-driven irrigation systems is underscored by documented evidence of increasing drought severity and water scarcity. Between 2001 and 2020, drought significantly affected Romanian arable land, with 2003 marking the driest year, impacting approximately 25.6% of agricultural areas (Dobri et al., 2021). Furthermore, long-term reconstructions using tree-ring oxygen isotopes from Letea Forest indicate frequent severe drought episodes over the past two centuries, particularly from 2007 to 2020, highlighting an intensified drought trend linked to climate variability and large-scale atmospheric circulation patterns (Nagavciuc et al., 2025). Additionally, Romania faces escalating desertification risks, especially in its southern and eastern regions, with projections indicating significant worsening by 2030 due to reduced precipitation and increasing temperatures (Ministry of Environment, 2019). Moreover, the World Bank's drought risk assessment confirms that drought conditions in Romania have intensified notably since 1980, severely impacting agriculture and water availability (World Bank, 2025). These factors and infrastructural challenges and inefficient traditional irrigation methods underline the critical need for advanced, sustainable irrigation management technologies.

MATERIAL AND METHOD

This research article employs a comprehensive and systematic analysis of relevant scientific literature and authoritative institutional reports to compare traditional irrigation practices with advanced AI-driven irrigation systems, particularly emphasizing their applicability in Romanian agriculture. Initially, the study focuses on the limitations of traditional irrigation methods such as flood and manual sprinkler systems, widely recognized for their inefficiencies, high water consumption, and vulnerability to climatic variability.

Further analysis considers the intensifying impact of climate change, which exacerbates existing irrigation challenges through increased evapotranspiration rates, altered precipitation patterns, and prolonged drought episodes.

To contextualize the urgency of adopting AI-driven solutions in Romania, specific national-level studies were reviewed. Notably, satellite-based research employing the Normalized Difference Drought Index (NDDI) has demonstrated a substantial increase in drought severity and frequency on Romanian agricultural lands between 2001 and 2020 (Dobri et al., 2021). Complementing this, long-term drought reconstructions derived from oxygen isotope tree-ring analysis indicate historical patterns of persistent drought episodes in Romania, further highlighting the need for advanced irrigation management approaches in response to the increasing frequency and severity of drought events (Nagavciuc et al., 2025). Institutional reports from the Romanian Ministry of Environment and the World Bank further validate these findings by detailing extensive desertification risks, land degradation challenges, and growing drought vulnerability, reinforcing the necessity for integrated, technologically advanced irrigation management practices.

An extensive international scientific literature was examined to explore the practical application of artificial intelligence technologies within irrigation systems. Reviewed studies illustrate various AI approaches, including machine learning, deep reinforcement learning, and neural networks integrated with IoT technologies, significantly enhancing water-use efficiency and irrigation precision. Machine learning models, such as regression and decision-tree algorithms, have demonstrated exceptional capabilities in accurately predicting water demands, optimizing resource use, and improving crop productivity through precise agricultural management (Chlingaryan et al., 2018). Furthermore, advanced models based on deep reinforcement learning have provided dynamic irrigation scheduling solutions, effectively minimizing water waste and responding adaptively to fluctuating climatic conditions, leading to improved resource conservation and increased yield stability (Elavarasan & Vincent, 2020).

Additional insights were obtained from IoT-based studies, where integrating support vector machines (SVM) and neural networks into irrigation management systems resulted in automated, real-time irrigation control, significantly reducing human intervention and achieving substantial water savings (Goap et al., 2018). Further innovations include neural network-based water pumping systems that leverage IoT sensor data, demonstrating significant gains in both agricultural productivity and operational efficiency (Karar et al., 2020). The incorporation of transfer learning techniques into neural networks for smart irrigation also exemplifies AI's adaptability and efficiency in managing complex agricultural environments, highlighting its substantial potential to revolutionize traditional irrigation practices (Risheh et al., 2020).

Recognizing the importance of institutional support in the widespread adoption of AI technologies in agriculture, this research article also considers relevant European initiatives. Programs such as the European Green Deal and Horizon Europe actively promote sustainable agriculture through substantial financial backing, policy frameworks, and strategic support aimed explicitly at advancing precision agriculture, smart farming, and AI-driven solutions. Moreover, Europe's Digital Agricultural Strategy fosters digital transformation in agriculture by providing targeted funding and resources to support integrating AI and IoT technologies. These European-level programs present significant opportunities for Romania, facilitating technological transfer, capacity building, and implementing innovative agricultural practices in response to escalating climate-induced agrarian challenges.

The synthesis of these extensive scientific and institutional resources forms a robust analytical foundation, clearly identifying AI-driven irrigation systems' environmental, economic, and agricultural benefits.

RESULTS AND DISCUSSIONS

The global climate crisis has emerged as a significant threat to sustainable agriculture, placing unprecedented stress on water resources and irrigation systems worldwide. As global surface temperatures continue to rise at an accelerated pace—approximately 0.20°C per decade since 1982—agricultural systems have become increasingly vulnerable to severe climatic disruptions, notably prolonged droughts, erratic rainfall, and heightened evapotranspiration rates (Yuan et al., 2024). These climatic changes, driven predominantly by human activities such as extensive fossil fuel use, rapid population growth, and escalating greenhouse gas emissions, have directly compromised traditional agricultural practices and significantly reduced crop productivity (Fuentes et al., 2023).

One of the most immediate and severe impacts of climate change on agriculture is the intensification of drought conditions, which have exposed critical weaknesses in traditional irrigation systems, including flood and manual sprinkler methods. These conventional practices frequently result in substantial water losses due to evaporation, deep percolation, and runoff, exacerbating water scarcity and degrading soil health. Consequently, traditional irrigation methods often struggle to maintain agricultural productivity under increasingly unpredictable climatic conditions, highlighting the urgent need for more advanced and sustainable water management solutions.

In response to these pressing challenges, integrating artificial intelligence (AI) technologies, such as IoT sensor networks and machine learning algorithms, offers promising alternatives capable of significantly enhancing water-use efficiency and agricultural resilience. This research systematically evaluates existing scientific literature and practical implementations of these advanced technologies, specifically analyzing their effectiveness, sustainability, and economic viability compared to traditional irrigation approaches. By focusing on regions particularly vulnerable to drought, such as Romania, the analysis provides critical insights into the potential of AI-driven irrigation systems to mitigate climate-induced agricultural risks.

The systematic research process employed in this analysis, including literature selection criteria, data synthesis methods, and comparative frameworks, is illustrated in Figure 1 and 6, outlining the analytical steps undertaken to rigorously evaluate the comparative performance of traditional and AI-driven irrigation methods.

Romania's agriculture sector has increasingly experienced the direct and severe impacts of climate change, primarily manifested through intensified drought episodes, erratic rainfall, and heightened evapotranspiration rates. Recent studies highlight these climatic trends, underscoring their significant implications for traditional irrigation practices.

The increasing unpredictability of climatic conditions in Romania has had a profound impact on agricultural productivity, particularly due to extended drought periods and erratic precipitation patterns. Research conducted in the Crișurilor Plain has revealed that drought variability has negatively influenced staple crops such as wheat, maize, and cabbage. Specifically, studies have identified a strong correlation between the Palfai Aridity Index (PAI) and maize production, with significant yield reductions occurring in years of severe drought (Sabău et al., 2002)

Additionally, irrigation has proven essential in mitigating the adverse effects of soil moisture deficits on crop performance. Findings from cabbage cultivation trials in the Crișurilor Plain indicate that inadequate water availability leads to substantial yield reductions. However, strategic irrigation implementation has been shown to enhance production by 153% while improving water use efficiency by 60% (Domuța et al., 2017). These insights underscore the necessity of refining irrigation techniques, where emerging AI-driven technologies could offer valuable solutions for optimizing water distribution and ensuring sustainable agricultural practices in the future.

An extensive analysis covering the period 2001–2020, utilizing the Normalized Difference Drought Index (NDDI)—a satellite-based indicator assessing vegetation moisture and drought severity—demonstrated a marked increase in drought frequency and intensity across Romania, particularly in southern and southeastern agricultural regions (Dobri et al., 2021). The NDDI is critical for monitoring drought impacts as it integrates vegetation condition with moisture availability, providing precise spatial and temporal drought assessments essential for informed agricultural management.

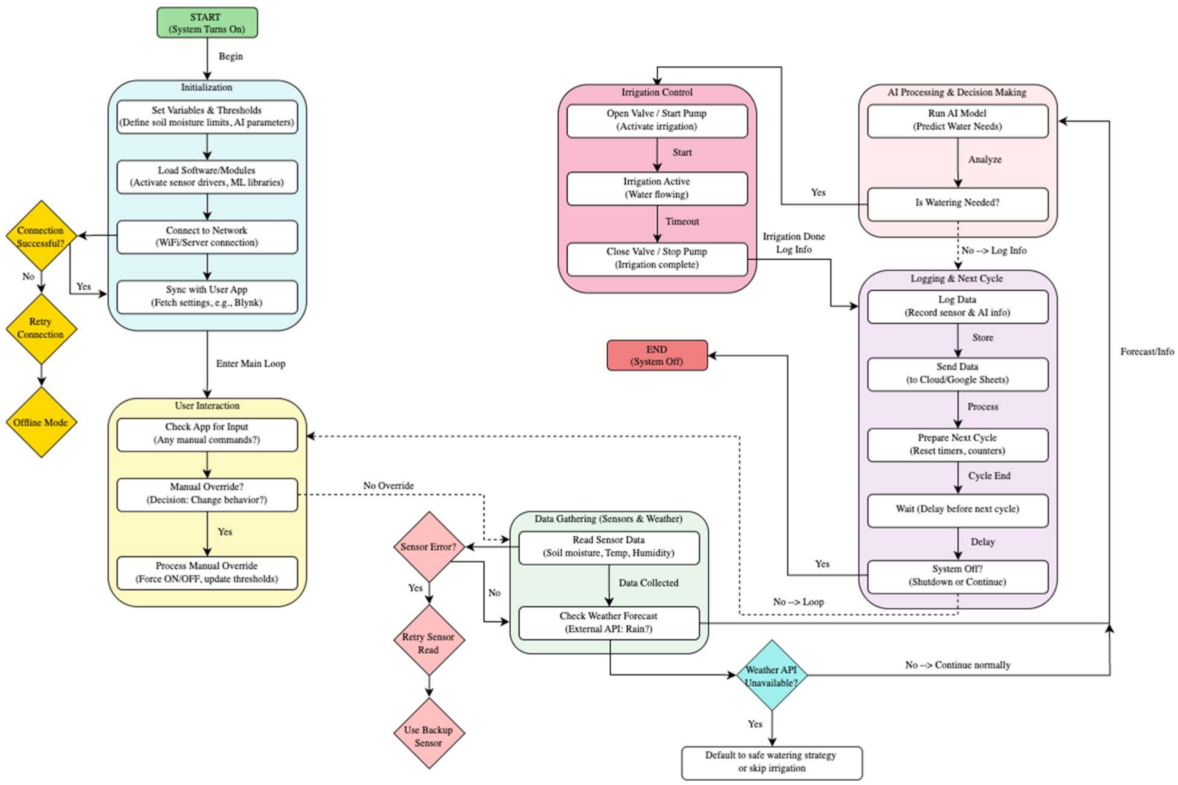

Figure 1 **Flowchart representing the procedural framework for the systematic review and subsequent analytical stages**

Complementing these contemporary findings, historical drought reconstructions using dendrochronological methods based on oxygen isotopes from tree rings revealed that the recent intensification of drought conditions is part of a broader, escalating climatic trend spanning centuries (Nagavciuc et al., 2025). This long-term analysis confirms that recent drought events are unusually severe and persistent compared to historical norms, indicating a significant climatic shift toward more extreme and sustained drought periods in Romania.

Additional institutional evaluations support these findings, highlighting severe environmental and agricultural threats. The Romanian Ministry of Environment's strategic environmental report emphasizes an increased risk of desertification and extensive land degradation directly linked to prolonged drought periods (Ministry of Environment, 2019). Similarly, the World Bank's comprehensive drought risk assessment underscores Romania's heightened vulnerability, projecting further intensification of drought impacts without substantial adaptation and mitigation measures (World Bank, 2025). Given the historical and predicted increase in drought conditions, traditional irrigation methods such as flood irrigation and manual sprinklers face critical limitations. These traditional approaches are inherently vulnerable to drought, characterized by high water losses due to evaporation, runoff, and inefficient water distribution. Consequently, Romania's agricultural practices urgently require advanced irrigation solutions that respond adaptively and efficiently to ongoing climatic changes.

Traditional irrigation systems, including flood irrigation and manual sprinkler methods, have been widely used in agriculture for centuries. While these methods provide a simple and low-cost approach to water distribution, they suffer from significant inefficiencies that make them increasingly unsuitable under modern climate conditions. High water losses due to evaporation, percolation, and surface runoff, combined with their limited adaptability to changing climatic patterns, pose major challenges for sustainable agricultural water management.

One of the primary limitations of traditional irrigation is water loss through evaporation. In flood irrigation, large volumes of water are applied directly to fields, often during peak daytime temperatures, leading to excessive evaporation before plant roots can effectively absorb water. Similarly, manual and overhead sprinkler systems spray water over crops to expose them to atmospheric heat and wind, resulting in substantial moisture loss before it reaches the soil. Studies have shown that evaporation losses in arid and semi-arid regions, such as southern Romania, can account for up to 50% of total irrigation water applied, drastically reducing water-use efficiency and contributing to long-term water scarcity (Dobri et al., 2021).

Another major issue is deep percolation losses, where excess irrigation water seeps beyond the root zone into deeper soil layers, making it inaccessible to crops. This problem is particularly pronounced in sandy or loosely compacted soils, where water infiltration rates are high. In regions with poor water retention capacity, such as parts of Romania's agricultural belt, excessive percolation not only wastes valuable water resources but also leaches nutrients from the soil, reducing soil fertility and increasing dependence on artificial fertilizers. Surface runoff is another common inefficiency in traditional irrigation systems. Flood irrigation, which relies on large quantities of water flowing across fields, often results in excessive runoff, particularly on uneven terrain or compacted soil surfaces where absorption rates are low. This runoff not only wastes water but also contributes to soil erosion, washing away topsoil layers rich in organic matter and essential nutrients. Over time, erosion depletes the land’s agricultural potential, leading to declining crop yields and increased vulnerability to extreme weather events.

Precision is another critical limitation of traditional irrigation. Manual methods rely on visual assessments and farmer intuition to determine watering schedules, leading to frequent over-irrigation or under-irrigation. Over-irrigation can waterlog the soil, creating anaerobic conditions that reduce root oxygen availability, increase the risk of fungal diseases, and encourage weed proliferation. Conversely, under-irrigation results in crop water stress, reduced biomass production, and lower yields. Without real-time data and automated control mechanisms, traditional irrigation methods fail to optimize water distribution efficiently, making them unreliable in increasingly erratic climate conditions (Nagavciuc et al., 2025).

From an economic perspective, traditional irrigation is associated with high operational costs due to inefficiencies in water use and the labor-intensive nature of manual scheduling. Farmers relying on conventional irrigation often experience higher expenses in terms of water usage, energy consumption for pumping, and additional costs for fertilizer replenishment due to nutrient leaching. In contrast, modern AI-driven irrigation systems demonstrate significant cost savings by precisely delivering water only where and when it is needed, optimizing resource efficiency. Scalability presents another major challenge. Traditional irrigation methods lack the ability to adapt to large-scale agricultural operations or to adjust dynamically based on real-time climatic conditions. As water scarcity worsens, regions with limited water availability require irrigation systems that can efficiently manage and allocate resources at scale. Traditional methods do not integrate predictive analytics or remote sensing capabilities, making them increasingly impractical for modern, large-scale, and climate-resilient farming.

Given these limitations, adopting advanced, AI-driven irrigation technologies becomes a necessity rather than a choice. These modern systems, equipped with IoT sensors and predictive models, minimize water losses by optimizing application timing and precision, significantly reducing inefficiencies inherent in traditional methods. Unlike manual and conventional irrigation techniques, which rely on estimates and static schedules, AI-based irrigation systems integrate real-time data collection, predictive modeling, and automation to optimize water distribution dynamically. These technologies leverage IoT sensors, machine learning algorithms, and cloud-based analytics to ensure that crops receive the exact amount of water they need at the right time, significantly reducing waste and improving yields.

One of the primary advantages of AI-driven irrigation is its water-use efficiency. Traditional irrigation methods, such as flood irrigation and manual sprinklers, suffer from high losses due to evaporation, percolation, and runoff, often wasting 30–50% of applied water (Chlingaryan et al., 2018). In contrast, AI-powered systems use real-time soil moisture sensors to monitor water availability in the root zone and weather prediction models to anticipate rainfall, thereby adjusting irrigation schedules dynamically. This precision irrigation technique has been shown to reduce water usage by up to 50% while maintaining or increasing agricultural productivity (Elavarasan & Vincent, 2020). Additionally, AI-driven irrigation systems demonstrate substantial improvements in crop yield and quality. Studies on machine learning-based irrigation scheduling have found that optimizing water delivery using AI leads to 15–25% higher crop yields than conventional methods (Goap et al., 2018). This is due to improved nutrient retention, reduced water stress, and a more stable microclimate around plants, ensuring consistent growth conditions. Furthermore, integrating remote sensing technologies, such as satellite imagery and drones, enhances precision by identifying crop-specific water requirements, allowing customized irrigation plans tailored to different plant types and soil conditions (Karar et al., 2020).

An outstanding example is the T-irrigation system, developed by Topraq, which incorporates cutting-edge features designed to revolutionize agricultural practices. This advanced system utilizes smart irrigation technology to provide real-time data on underground conditions, ensuring full-field visibility, efficient resource management, reduced waste of essential inputs, enhanced energy conservation, and long-term agricultural sustainability. Additionally, it is equipped with a suite of sophisticated sensors, including rainfall detectors, water pressure monitors, ultrasonic flowmeters, and GPS, enabling precise control and seamless pivoting of irrigation systems.

T-Irrigate combines real-time sensor data and weather forecasts with an advanced irrigation model to supply water precisely based on soil, crop, and environmental needs. Using AI to analyze factors like soil moisture, temperature, and humidity, it determines optimal schedules and adapts to crop growth, soil conditions, and seasonal changes. This efficient system reduces waste, conserves water, and boosts crop yields through innovative smart irrigation.

Figure 2 **T-irrigate system and its components**

Figure 3 **The Topraq app efficiently monitors and manages key agricultural parameters**

Another instance is CropX, which leverages real-time data from soil sensors and Actual ET metrics to generate predictive insights. This allows farmers to take preemptive measures and ensures constant awareness of whether a field's moisture levels are ideal, excessive, or deficient.

Figure 4 **CropX sensor**

An additional example is the 360 RAIN autonomous irrigation robot, equipped with a 24 HP diesel engine and advanced GPRS navigation, ensuring comprehensive coverage of intricate agricultural plots while maximizing irrigation efficiency across 80 to 350 hectares and minimizing resource use.

Figure 5 **360 Rain irrigation robot**

The economic benefits of AI-based irrigation systems are equally significant. While the initial investment in AI-enabled irrigation infrastructure (such as IoT sensors, data servers, and automation controllers) can be higher than traditional methods, the long-term operational savings are substantial. By reducing water waste, lowering energy costs for pumping, and minimizing fertilizer runoff, AI-driven irrigation can cut irrigation costs by up to 30%, leading to higher profit margins for farmers. In high-value crop production, where precision water management directly affects product quality, AI-based irrigation strategies have resulted in higher market value and reduced losses due to drought stress (Elavarasan & Vincent, 2020).

Beyond economic efficiency, environmental sustainability is a key advantage of AI-integrated irrigation. Traditional methods contribute to soil degradation, increased salinity, and groundwater depletion due to excessive and poorly managed water application. AI-driven systems, by contrast, help prevent over-irrigation, reducing soil erosion and maintaining the long-term fertility of agricultural land. Additionally, smart irrigation minimizes the extraction of groundwater resources, ensuring long-term sustainability in regions facing severe drought conditions.

Real-world applications further illustrate these advantages. In Spain, where water scarcity is a persistent issue, AI-powered irrigation solutions have cut water consumption by 45% in vineyards and olive groves while increasing crop yields by 20%. In India, IoT-integrated smart irrigation platforms have reduced irrigation times by 30% while ensuring optimal soil moisture levels, resulting in higher cotton and wheat production (Goap et al., 2018). Similar results were observed in Australia, where AI-based irrigation management systems reduced agricultural water use by 50% in drought-prone areas, contributing to better water conservation strategies at a national level (Chlingaryan et al., 2018).

The scalability of AI-driven irrigation also makes it a viable solution for large-scale farming operations. Unlike traditional irrigation, which requires manual labor-intensive adjustments, AI-driven systems can autonomously adjust irrigation schedules based on real-time feedback, making them suitable for both small farms and industrial-scale agricultural enterprises. Moreover, as climate change exacerbates water shortages, integrating AI-driven decision support systems (DSS) will become increasingly essential for sustainable agricultural practices.

With these clear benefits in efficiency, precision, economic returns, and sustainability, AI-powered irrigation is emerging as the most viable long-term solution for modern water management in agriculture. Moving forward, further advancements in AI, big data analytics, and sensor technology will continue to refine these systems, ensuring that farmers can maximize productivity while preserving essential water resources. AI-driven irrigation relies on Internet of Things (IoT) sensor networks to collect and analyze real-time environmental and soil data, enabling precise water management. These sensor-based systems continuously monitor soil moisture, temperature, humidity, and salinity, which are crucial for determining crop water requirements. Unlike traditional irrigation systems that operate on fixed schedules, AI-enabled irrigation dynamically adjusts water distribution, reducing both over-irrigation and crop water stress.

The integration of wireless communication protocols, such as LoRaWAN (Long Range Wide Area Network) and NB-IoT (Narrowband IoT), facilitates efficient data transmission from distributed sensors to centralized cloud platforms. LoRaWAN is particularly beneficial for large-scale farms due to its long-range, low-power communication capabilities. At the same time, NB-IoT is optimized for urban and greenhouse irrigation applications where high data transmission reliability is required. The real-time transmission of environmental data allows AI models to analyze trends, predict water requirements, and automate irrigation processes, significantly improving water-use efficiency.

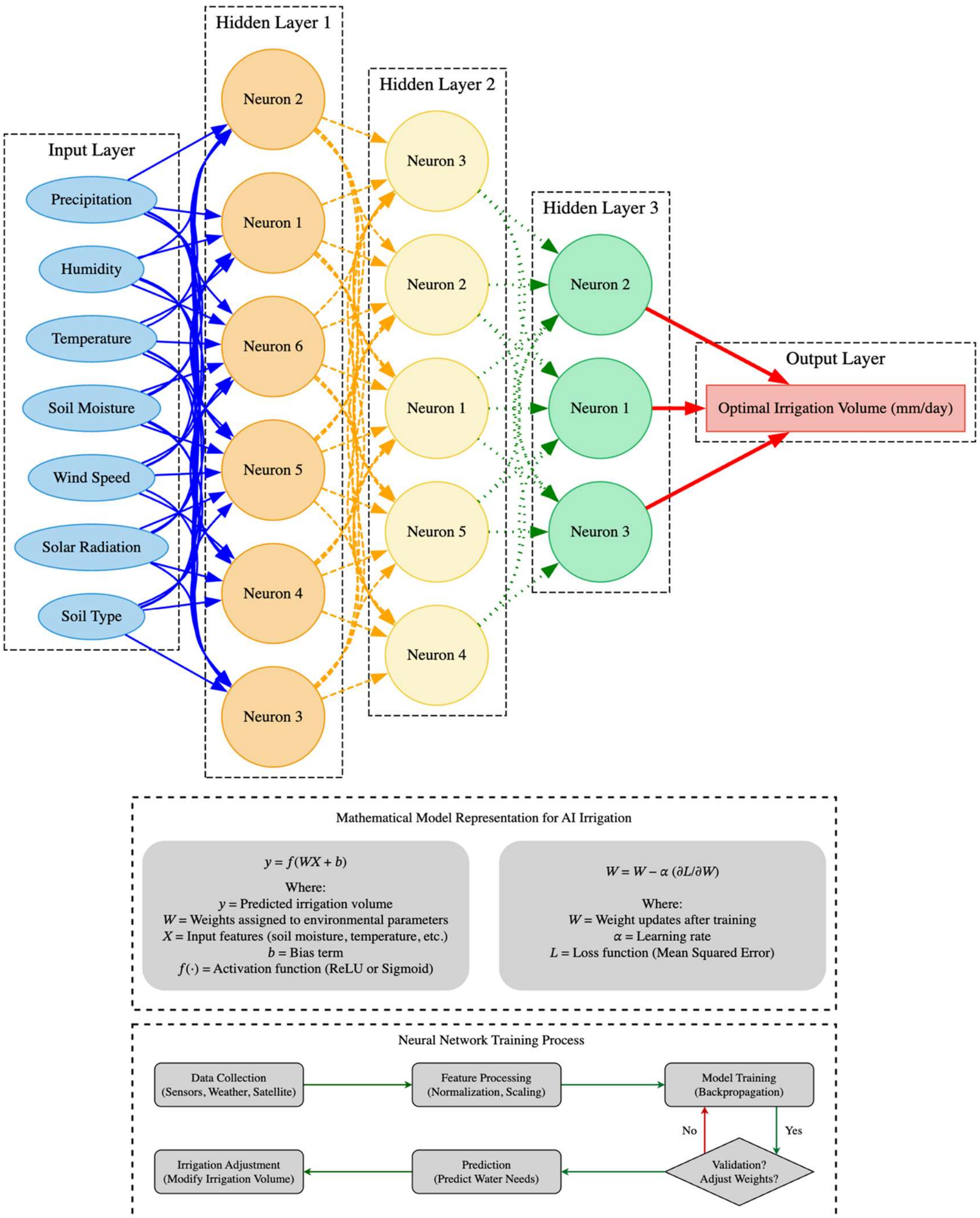

Figure 6 **Flowchart showcasing the methodology and sequential stages of the systematic review process**

CONCLUSIONS

The integration of Artificial Intelligence (AI) in irrigation management represents a crucial advancement in enhancing water-use efficiency, ensuring sustainable agricultural practices, and mitigating the adverse effects of climate change. This research article demonstrates that AI-driven irrigation systems significantly outperform traditional irrigation methods, particularly in Romania, where increasing drought frequency, erratic precipitation, and escalating desertification risks threaten agricultural productivity and food security.

These technologies enable precise and adaptive irrigation scheduling, reducing inefficiencies associated with conventional irrigation methods such as flood and manual sprinkler systems. By dynamically adjusting water distribution, AI-driven irrigation has been shown to reduce water consumption by up to 50% while increasing crop yields by 15–25%.

Neural network-based models and reinforcement learning techniques further enhance irrigation precision by continuously learning from environmental data, optimizing resource allocation, and accurately predicting future water needs.

Despite its proven advantages, adopting AI-driven irrigation in Romania faces several challenges, including limited digital infrastructure, financial constraints, and a lack of technical expertise among farmers. Overcoming these barriers requires strong governmental support, economic incentives, and targeted digital literacy programs to facilitate the transition from traditional to smart irrigation practices.

European initiatives provide essential financial and technological support, fostering the large-scale adoption of AI in agriculture. These programs offer funding, policy frameworks, and technological resources that can help Romania implement precision irrigation solutions tailored to its climatic and agricultural conditions. Moving forward, further advancements in AI algorithms, big data analytics, and remote sensing technologies will continue to refine smart irrigation, enhancing both water conservation and crop productivity. With continued investment in AI research, cross-sector collaborations, and farmer training programs, AI-driven irrigation has the potential to revolutionize agricultural water management, ensuring long-term sustainability, economic efficiency, and resilience against climate-induced water shortages.

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