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Optimizing micro irrigation efficiency in water-scarce agroecosystems using AI and remote sensing technologies

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Abstract

In dryland farming, water shortages require creative irrigation solutions. In dry and semi-arid areas, drip, sprinkler, and subsurface irrigation are becoming more popular to maximize water use. These systems still struggle to distribute water efficiently, use a lot of energy, and make real-time decisions. Using AI and remote sensing to overcome these restrictions is revolutionary. AI-driven irrigation systems use machine learning algorithms, predictive analytics, and IoT-enabled smart sensors to maximize water use, minimize waste, and increase crop yields. UAVs, satellites, and multispectral imaging are remote sensing technologies. These technologies enable real-time soil moisture, evapotranspiration, and plant health monitoring. For site-by-site water management, GIS, AI, and remote sensing improve precise irrigation. This review examines the pros, cons, and future uses of artificial intelligence (AI) for remote sensing and automated irrigation in dryland farming using recent studies. Comparing current studies shows that wide adoption requires better policy frameworks, sensor networks, and AI algorithms. It also identifies key research gaps. The results show that we need better water management technology and approaches from different fields to sustain farming. Future research should expand remote sensing in small-scale farming, incorporate blockchain for data security, and develop affordable AI-driven irrigation models. To implement policies and infrastructure widely, policymakers and stakeholders must collaborate. Researchers, agronomists, and lawmakers who want to improve irrigation efficiency with AI and remote sensing will benefit from this study.

Keywords: Micro-irrigation, remote sensing, smart agriculture, precision irrigation, dryland agriculture

Introduction

Dryland agriculture faces water scarcity due to high evaporation and unpredictable precipitation, making water efficiency essential for long-term crop production. Micro-irrigation using drip and sprinkler systems has become an important water-saving tool. Plant roots receive specific amounts of water directly. In traditional irrigation methods, water is often not distributed efficiently and resources are wasted because of set schedules and monitoring that has to be done by hand. AI and remote sensing have made it possible for dryland farming solutions that are based on data. This has completely changed how irrigation is managed. Irrigation systems that are powered by AI use machine learning algorithms, IoT sensors, and predictive analytics to keep real-time track of the weather, crop water needs, and soil moisture. By making decisions automatically, these smart systems make sure that crops get the right amount of water at the right time and reduce water loss. UAV hyperspectral images, satellite images, and Geographic Information Systems (GIS) all help with precise irrigation by showing how water is spread out in the soil, how healthy plants are, and how quickly plants lose water through evaporation. With AI and remote sensing, you can always keep an eye on things and find ways to save water by changing how you water based on the weather. A new study says that AI and remote sensing can make micro-irrigation work better in dry and semi-dry areas. To save water and make crops last longer, (Wei *et al.*, 2024) ^[17] weigh the pros and cons of AI-driven irrigation. (Wang *et al.*, 2024) ^[10] talk about how machine learning and remote sensing can help farmers use data to decide when to water their crops, which makes precision agriculture better. AI can figure out how much water and energy sensor-based micro-irrigation systems should use, as shown by more research like that by (Mohammed *et al.*, 2023) ^[13].

Even with these changes, there are still issues with how much it costs to implement, how accurate the data is, and how many farmers need to be taught. There is a lot of information in this review about how AI and remote sensing can be used to improve micro-irrigation for dryland farming. In places that don't get a lot of water, smart irrigation systems make things grow better and last longer. This paper looks at what has already been written and talks about problems, trends, and possible new research.



Micro Irrigation in Dryland Agriculture

Micro-irrigation, which delivers water directly to plant roots, reduces evaporation and runoff. It excels in dryland farming (Vaijnath Kantiram Chavan *et al.*, 2024) ^[19], where unpredictable rainfall and water scarcity make crop production difficult. Micro-irrigation uses drip, subsurface, and sprinkler irrigation. Drip irrigation conserves water and maintains soil moisture (Ahmed *et al.*, 2023) ^[1]. Through emitters, water is slowly released into the soil around plant roots. Pressurized nozzles in sprinkler irrigation cover larger areas and simulate rainfall (Patel *et al.*, 2023) ^[14]. Subsurface irrigation uses buried tubing to deliver water directly to plant roots, reducing surface evaporation and increasing water efficiency (Alharbi *et al.*, 2024) ^[2].

Many dry and semi-arid regions benefit from micro-irrigation. Evaporation and deep percolation losses are reduced, improving water-use efficiency and agricultural yields (Xing & Wang, 2024) ^[10]. Micro-irrigation saves soil fertility and promotes sustainable agriculture by reducing erosion and nutrient leaching. (Bwambale *et al.*, 2022) ^[5] say these systems help farmers in water-scarce areas grow crops more precisely by channelling water to specific areas. Micro-irrigation systems have pros and cons. Some smallholder farmers cannot afford drip and subsurface irrigation due to their high installation costs (Gaznayee *et al.*, 2023) ^[8]. Emitter blockage and system wear increase operational costs and complexity (Lakhiar *et al.*, 2024) ^[10].

Role of AI in Micro Irrigation Management

Micro-irrigation management is changing because artificial intelligence (AI) is making it easier to accurately distribute water. This is making things more efficient and cutting down on waste. The best use of water can be found through AI-driven scheduling and automation for irrigation that checks and analyses things like soil moisture, temperature, and weather forecasts all the time. Most irrigation systems have set times for when they should work (Mohammed *et al.*, 2023) ^[13] but AI-based systems change when they water plants based on what they need. (Wei *et al.*, 2024) ^[17] say

that these smart systems use data from sensors and past weather records to figure out how much water dryland farms will need for irrigation. This helps farmers make better use of water. In order to make irrigation models, machine learning (ML) and predictive analytics look at very large datasets. This is an important part of taking care of water. Based on data from sensors on the ground, remote sensing technologies, and satellite images, Xing and (Wang 2024) ^[10] say that ML algorithms can accurately guess how much water plants need. Farmer can use these models to make smart choices that will help them stay away from water stress and over-irrigation. (Ashoka *et al.*, 2024) ^[3] say that decision support systems that are powered by AI can also suggest the best way to water crops based on their type, the texture of the soil, and the rate at which they lose water through evaporation and transpiration. (Tan *et al.*, 2024) ^[15] say that these kinds of predictive analytics help make the best use of water and also help with sustainable farming by lowering the use of resources and increasing crop yields. Intelligent sensors and the Internet of Things (IoT) make farming even more accurate. According to a study by (Yacoob *et al.*, 2024) ^[20], weather stations, drones, and sensors that measure soil moisture are used by irrigation networks built on the Internet of Things (IoT) to keep track of real-time field conditions. These sensors report data to cloud-based platforms. An algorithm using artificial intelligence would then look at it and set up automatic irrigation. According to (Wiang *et al.*, 2024), smart irrigation controllers change how much water plants get based on the soil to keep them from getting too wet or too dry. Efficiency in water utilization, cost reduction, and improved sustainability in dryland agriculture are all achieved through the real-time monitoring capability of these systems (Mmbando, 2025) ^[12]. Multiple case studies have shown that micro irrigation based on AI works. According to (El-Gindy *et al.*, 2024) ^[6], AI-powered irrigation models have diminished the quantity of water used by as much as 30% in dry areas without affecting the production of crops. One study from 2024 by Tan *et al.* says that cotton fields used a lot more water more efficiently by using UAV-based hyperspectral remote sensing and AI to find out how wet the soil was and improve irrigation. The way micro-irrigation is managed could be completely changed by AI, as shown by these new developments. There is good news about how farming can survive and adapt to climate change in the long term.

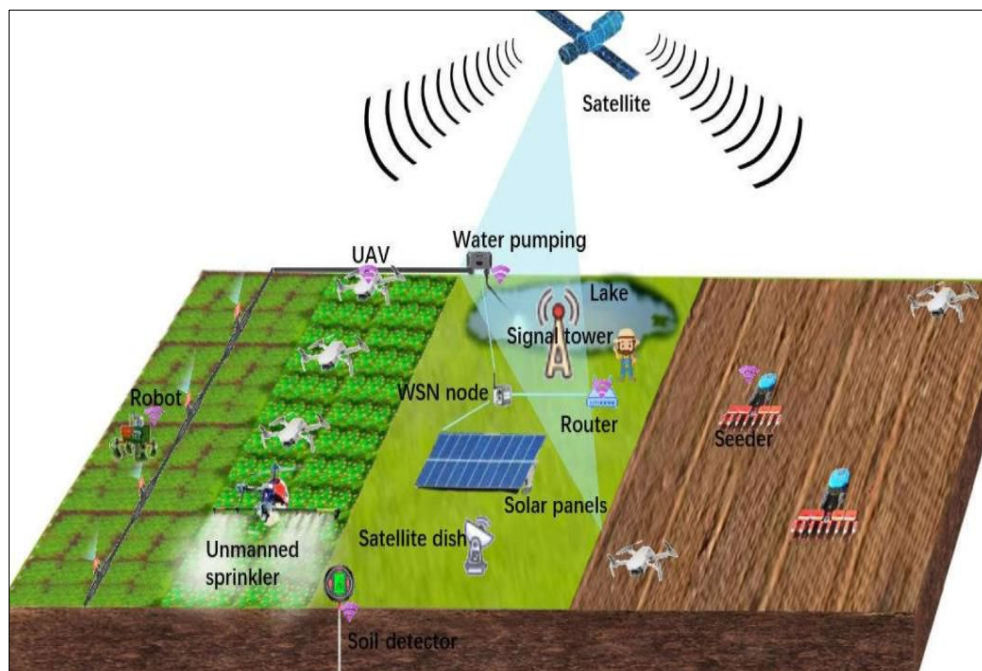
Synergistic Approach: AI and Remote Sensing Integration

With remote sensing, it's easier to figure out how to water farms that are in dry areas. These technologies let you know about the weather, crop health, and soil moisture in real time. A study by (Zhang *et al.*, 2023) says that precise field monitoring and irrigation are made possible by drones, UAVs, and satellites. Using satellites, (Huang *et al.*, 2024) say that Sentinel-2, MODIS, and Landsat keep an eye on large areas of vegetation and soil moisture. This helps farmers figure out when to water their crops. A study by (Ali *et al.*, 2024) ^[15] says that high-resolution data from UAVs and drones with high-tech imaging sensors lets water resources be managed and studied in the field. It is very important to use multispectral and hyperspectral imaging to find out about crop water stress and soil moisture. (Sharma *et al.*, 2024) ^[3] say that NIR and SWIR reflectance can be

used by multispectral sensors to measure the amount of water in plants and soil. A study by (Li *et al.*, 2023) says that hyperspectral imaging can pick up hundreds of spectral bands. This helps us figure out how healthy a plant is and how much water it needs. A lot of work can be done with targeted irrigation. (Gao *et al.*, 2024) say that these imaging technologies can help farmers find dry spots on their land and water them so that they get more crops and waste less water.

Remote sensing and GIS work together to make irrigation more accurate by letting you see how water is spread out and how the soil is formed. With GIS tools that work with satellite and UAV data (Wang & Chen, 2024) ^[10], you can accurately map changes in soil moisture, rates of evaporation, and soil water needs. By putting together GIS-based models and remote sensing data, (Xie *et al.*, 2024) say

that farmers can make irrigation plans that are specific to their land, use water more efficiently, and take less damage to the environment. It is said by (Patel *et al.*, 2024) that this type of integration works best in semi-arid and dry areas where water is scarce and crops need to be watered. Remote sensing is a good way to water dry land. A study by (Verma *et al.*, 2023) found that mapping soil moisture with remote sensing made it easier to plan irrigation in Rajasthan, India. This used 25% less water and didn't hurt crop yields. UAVs have used hyperspectral imaging to keep an eye on vineyards in the Central Valley of California that are having trouble with water. This has helped find places that need watering and make the grapes better (Rodriguez *et al.*, 2024) ^[17]. These examples show how remote sensing is making farming better for the environment and water-wise by making it easier to run irrigation systems.



Comparative Analysis of Existing Studies

A new study on irrigation has shown that AI and remote sensing can help farmers grow more crops more accurately and make better use of water resources. (Singh *et al.*, 2023) say that AI-driven irrigation systems use machine learning algorithms and predictive analytics to use real-time data to make better use of water and automate scheduling for irrigation. (Patel *et al.*, 2024) say that UAVs, satellite images, and multispectral or hyperspectral imaging are used to find out how much water is in the soil, how much water is lost through evaporation, and how stressed crops are about water. AI models help people in charge of irrigation make choices, but (Li *et al.*, 2023) say that remote sensing makes the models more accurate.

More than one study has used AI and remote sensing to find the best way to water plants. Zhang *et al.* made an AI-powered model in 2023 that could find the best times to water semi-arid areas. A satellite's reading of how wet the ground was used in the model. (Gao *et al.*, 2024) trained deep learning models with UAV hyperspectral images so they could find early signs of crop water stress. These studies show that AI can help manage water, but for predictions to be correct, they need high-quality datasets. In a different study from 2024, Wang and Chen looked at how to use GIS and remote sensing to plan irrigation for specific sites. Researchers cut the amount of water used by 30% without having any effect on crop yields.

Table 1: Recent Applications of AI and Remote Sensing Technologies in Precision Irrigation Management

Study	Technology Used	Methodology	Key Findings
(Zhang <i>et al.</i> , 2023)	AI & Satellite Remote Sensing	AI-driven irrigation scheduling using satellite soil moisture data.	Improved irrigation efficiency in semi-arid regions.
(Gao <i>et al.</i> , 2024)	Deep Learning & UAV Hyperspectral Imaging	AI model trained on hyperspectral images for crop water stress detection.	Early identification of drought stress, improving water-use efficiency.
(Wang & Chen 2024) ^[10]	GIS & Remote Sensing	GIS-based spatial analysis with remote sensing data for irrigation planning.	30% reduction in water use while maintaining yields.

Future Prospects and Research Directions

Future agriculture technologies like AI-driven irrigation and remote sensing can improve water efficiency and sustainability. AI advances in deep learning models, real-time sensor data, and predictive analytics should improve precision irrigation. Artificial intelligence-powered irrigation systems will adapt to changing soil moisture and weather (Sharma *et al.*, 2024) ^[3]. AI-driven decision support systems will integrate weather forecasts, crop growth models, and real-time field data to dynamically optimise water usage (Patel *et al.*, 2023) ^[14]. Remote sensing technologies are also changing irrigation management. Hyperspectral imaging, UAV-based multispectral sensors, and high-resolution satellite imagery will improve soil moisture estimation and crop health monitoring (Li *et al.*, 2024) ^[15]. In overcast weather, new synthetic aperture radar (SAR) systems will improve water content detection for 24/7 tracking. Remote sensing and IoT devices like soil moisture probes and climate sensors can improve irrigation (Wang & Chen, 2024) ^[10].

Even with these technological advances, agriculture needs policies and infrastructure for AI-driven irrigation and remote sensing. Governments and agricultural agencies should implement policies to make AI models more transparent, standardize sensor networks, and encourage data sharing, according to (Zhang *et al.*, 2024) ^[10]. Cloud computing, edge AI processing, and affordable smart irrigation systems are needed to support small and medium-scale farmers. Training and digital literacy programmes should help farmers use these cutting-edge technologies. (Xie *et al.*, 2024) recommend developing affordable remote sensing solutions for smallholder farmers, integrating AI with blockchain for secure irrigation network data sharing, and studying hybrid AI models that combine physics-based hydrological models with machine learning. Filling these knowledge gaps will enable a more efficient and environmentally friendly irrigation system, saving water and increasing agricultural yields.

Conclusion

Irrigation management systems that use AI and remote sensing may make better use of water, better use of resources, and more sustainable farming. Smart irrigation systems that are powered by AI use sensor data in real time, automated scheduling, and predictive analytics to better distribute water. This makes less water waste and more crop yields. GIS integration, satellite imagery, and UAVs can help farmers figure out the best way to water their crops by showing them how much water is in the soil, how healthy the crops are, and how the weather changes. If AI and remote sensing are to be used in farming, farmers need open technology, standardized data, and money for R&D. The use of smart irrigation technology will grow faster if infrastructure investments are made in cloud computing and connecting things to the Internet of Things, and farmers are given financial incentives to do so. With AI models that are more accurate, researchers can lower the cost of remote sensing and come up with new ways to use older hydrological models with AI.

AI and satellites can help farmers get more done with their land, save money on inputs, and improve irrigation. Small and medium-sized farmers need to get training and computer programs to learn how to use these high-tech tools. Government agencies, agricultural experts, and tech

developers should work together to fill in the gaps in our knowledge and get more people to use new technologies. Last but not least, AI and remote sensing are making management of irrigation more effective and scalable, which is good for farming in the long term. Through research and smart investments, precision irrigation will get better. Even though it's not cheap, easy to get to, or backed by strong policy, this technology will save water and keep food safe in a climate that is changing.

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