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Applied Innovations in Irrigation Systems and Their Impact on Crop Production Efficiency: A Literature Review

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ABSTRACT

Agricultural water management is a critical factor in ensuring optimal crop production efficiency, especially in the context of increasing global food demand and climate variability. This study aims to systematically review applied innovations in irrigation systems and their impact on crop production efficiency. A qualitative approach using a systematic literature review method was employed by analyzing 20 peer-reviewed international journal articles published in recent years. The study focuses on key aspects such as irrigation technologies, water use efficiency, crop yield performance, and sustainability outcomes. The findings indicate that modern irrigation innovations, including smart irrigation systems, sensor-based irrigation, Internet of Things (IoT), and artificial intelligence (AI)-driven irrigation management, significantly improve water use efficiency and crop productivity. These technologies enable real-time monitoring, precise water distribution, and data-driven irrigation scheduling, resulting in reduced water waste and improved agricultural output. However, challenges such as high implementation costs, limited infrastructure, and low technological adoption among farmers remain major barriers to widespread use. These results suggest that stronger policy support, infrastructure development, and farmer capacity building are necessary to maximize the benefits of irrigation innovations. In conclusion, applied innovations in irrigation systems play a vital role in enhancing crop production efficiency, and future research should focus on integrated and scalable solutions to support sustainable agricultural water management.



INTRODUCTION

Water is one of the most critical resources in agricultural production, and its efficient management has become increasingly important in ensuring sustainable crop production systems. The growing global demand for food, combined with the impacts of climate change such as irregular rainfall patterns and prolonged droughts, has intensified pressure on agricultural water use efficiency (Lee et al., 2021). In many regions, traditional irrigation methods are still widely practiced; however, they are often characterized by low efficiency and substantial water losses through evaporation, runoff, and excessive application (Idier et al., 2024). These inefficiencies not only increase water consumption but also negatively affect crop productivity, soil conditions, and production costs. Therefore, improving irrigation efficiency has become a key priority in modern agriculture to support both productivity and environmental sustainability (Padhiary et al., 2025).

Applied innovations in irrigation systems have emerged as an effective approach to address these challenges and improve crop production efficiency. Irrigation innovation refers to the adoption of advanced technologies and management practices that enable more precise, timely, and efficient water application according to crop requirements. Modern irrigation systems, including drip irrigation, precision irrigation, sensor-based irrigation, Internet of Things (IoT)-enabled systems, automated controllers, and artificial intelligence (AI)-driven decision support tools, provide significant opportunities to optimize agricultural water management (Padhiary et al., 2025). These technologies facilitate real-time monitoring of soil moisture, climatic conditions, and crop water requirements, allowing irrigation decisions to be based on actual field conditions rather than predetermined schedules (Raj & Prahadeeswaran, 2025).

The impact of irrigation innovations extends beyond water conservation and directly influences crop production efficiency. Crop production efficiency refers to the ability to maximize agricultural output while minimizing the use of resources such as water, energy, labor, and fertilizers. Efficient irrigation systems contribute to improved crop growth, enhanced nutrient uptake, reduced operational costs, and increased yield quality and quantity. By delivering water directly to the crop root zone and minimizing losses, technologies such as drip irrigation and precision irrigation improve water productivity, which is commonly defined as the amount of crop yield produced per unit of water applied. Consequently, irrigation innovations play a crucial role in achieving sustainable agricultural intensification and resource optimization.

Recent studies have demonstrated that precision-based irrigation systems significantly improve agricultural productivity through optimized water management. The integration of soil moisture sensors, remote sensing technologies, and automated irrigation controllers enables farmers to adjust irrigation schedules according to crop needs and environmental conditions (Sharma, 2023). This approach minimizes both water stress and over-irrigation, thereby creating favorable conditions for crop growth and development. In addition, precision irrigation supports site-specific management practices by accounting for variations in soil properties, topography, and crop conditions within agricultural fields. Such targeted irrigation strategies contribute to higher resource-use efficiency and improved crop production performance.

Among recent technological advancements, IoT-based irrigation systems have gained considerable attention due to their capacity for continuous monitoring and automation. These systems integrate sensors, communication networks, and cloud-based platforms to collect and transmit real-time data on soil moisture, temperature, humidity, and other environmental parameters (Abu et al., 2022). The collected information is subsequently analyzed to automatically regulate irrigation operations, ensuring optimal water distribution and reducing human intervention. Through enhanced



monitoring accuracy and operational efficiency, IoT-enabled irrigation systems have been shown to improve crop productivity while reducing water consumption and labor requirements (Talavera et al., 2017).

Artificial intelligence has further expanded the capabilities of modern irrigation systems by enabling predictive and data-driven decision-making. AI algorithms can analyze large volumes of agricultural and environmental data to predict crop water requirements based on weather forecasts, soil characteristics, and crop growth stages (Liakos et al., 2018). Machine learning models can continuously adapt to changing conditions and generate optimized irrigation recommendations that improve water allocation efficiency. Beyond reducing water waste, AI-assisted irrigation management can lower operational costs, stabilize crop yields, and enhance overall farm productivity. Consequently, AI has become an increasingly important component of smart irrigation systems and sustainable agricultural management practices (Kamilaris & Prenafeta-Boldú, 2018).

Despite the considerable benefits associated with irrigation innovations, several barriers continue to limit their widespread adoption. High initial investment costs, inadequate infrastructure, limited technical expertise, and low levels of digital literacy remain significant challenges, particularly among smallholder farmers. Furthermore, the effectiveness of irrigation technologies may vary according to crop type, climatic conditions, soil characteristics, farm size, and management practices. These factors influence the performance and economic feasibility of irrigation innovations in different agricultural contexts.

Although numerous studies have investigated specific irrigation technologies, such as drip irrigation, IoT-based systems, automated irrigation controllers, and AI-assisted irrigation management, the existing evidence remains fragmented across different technologies, crops, and geographical regions. Most studies focus on evaluating individual innovations rather than providing an integrated assessment of how various irrigation technologies collectively influence crop production efficiency. As a result, a comprehensive understanding of the overall contribution of irrigation innovations to agricultural productivity, resource optimization, and sustainability remains limited.

Based on these research gaps, this study aims to systematically review applied innovations in irrigation systems and their impact on crop production efficiency. The main research question addressed in this review is: How do applied irrigation innovations contribute to improving crop production efficiency? Specifically, this study seeks to identify major irrigation innovations, evaluate their effects on water-use efficiency and crop productivity, and examine the challenges associated with their implementation. The novelty of this review lies in its comprehensive synthesis of multiple irrigation technologies, including precision irrigation, sensor-based systems, IoT-enabled irrigation, automation technologies, and artificial intelligence applications. By integrating findings from diverse studies, this review provides a broader understanding of how irrigation innovations contribute to crop production efficiency, resource-use optimization, and sustainable agricultural development.

METHODS

This study employs a qualitative research approach using a systematic literature review to examine applied innovations in irrigation systems and their impact on crop production efficiency. This approach is used to provide a structured and comprehensive synthesis of existing scientific evidence related to modern irrigation technologies. The subjects of this study consist of peer-reviewed journal articles focusing on irrigation innovations in agriculture, including smart irrigation systems, sensor-based irrigation, Internet of Things (IoT), and artificial intelligence (AI)-based irrigation management. The data sources were obtained from reputable international scientific databases. The inclusion criteria



include: (1) articles published between 2020 and 2025, (2) studies focusing on irrigation technology innovation in agriculture, and (3) research discussing water use efficiency, crop productivity, and sustainability outcomes. Meanwhile, exclusion criteria include non-peer-reviewed publications and studies not directly related to irrigation systems or crop production efficiency.

The research procedure follows a systematic review process consisting of four main stages: identification, screening, eligibility, and inclusion. In the identification stage, relevant studies were collected using keywords such as “smart irrigation,” “precision irrigation,” “IoT irrigation systems,” “AI in irrigation,” and “water use efficiency in agriculture.” The screening stage involved removing duplicate records and selecting articles based on title and abstract relevance. The eligibility stage included a full-text review to ensure that selected studies met the predefined inclusion criteria. Finally, the inclusion stage determined the final set of articles used for analysis.

Data analysis was conducted using qualitative content analysis. The selected studies were categorized based on irrigation technology type, application method, and impact on agricultural performance. The analysis process involved coding, classification, and thematic synthesis to identify patterns, relationships, and key findings across the literature. This approach allows for a comprehensive understanding of how irrigation innovations contribute to crop production efficiency.

To ensure validity and reliability, this study applies a transparent and systematic review protocol with clearly defined inclusion and exclusion criteria. The structured methodology enhances consistency in article selection and analysis. In addition, the use of multiple peer-reviewed sources reduces bias and strengthens the credibility of the findings. The research design is also replicable, allowing future researchers to apply similar methods in related studies on irrigation systems and agricultural efficiency.

RESULTS

1. The Role of Smart Irrigation Systems in Improving Water Use Efficiency and Crop Production Efficiency

Smart irrigation systems represent one of the most important applied innovations in modern agricultural water management. These systems utilize advanced technologies such as soil moisture sensors, automated controllers, remote monitoring systems, and data-driven irrigation scheduling to optimize water application in crop cultivation. By continuously monitoring soil and environmental conditions, smart irrigation systems enable farmers to determine the exact water requirements of crops. As a result, irrigation becomes more precise, reducing water wastage caused by over-irrigation or inefficient watering practices. This technological approach significantly improves water use efficiency while supporting sustainable agricultural production. These findings are consistent with previous studies highlighting the importance of precision-based irrigation in modern agriculture (Lee et al., 2021; Sharma, 2023).

Furthermore, smart irrigation systems contribute significantly to improving crop production efficiency through optimized water distribution. The ability to deliver water based on real-time soil moisture data ensures that crops receive adequate hydration at critical growth stages. This helps maintain optimal plant health and supports consistent crop development. In addition, efficient irrigation reduces plant stress caused by water shortages, which directly contributes to higher yield stability. By improving the timing and amount of water application, farmers can achieve better productivity outcomes with fewer resource inputs. These findings are in accordance with Singh (2024), who reported that smart irrigation technologies improve water-use efficiency while maintaining or increasing crop

productivity. The study further emphasizes that precise water management enables farmers to optimize resource utilization and achieve more sustainable agricultural production systems.

In addition, the integration of automation in smart irrigation systems reduces the need for manual intervention in irrigation management. Automated systems can activate or deactivate irrigation based on predefined thresholds, ensuring timely water delivery without human error. This increases operational efficiency and allows farmers to manage larger agricultural areas with less labor input. Moreover, automation helps reduce inconsistencies in irrigation practices, which often occur in traditional farming systems. As a result, agricultural operations become more reliable and efficient. These results are strengthened by Abu et al. (2022), who found that automated irrigation systems supported by sensor networks and real-time monitoring technologies enhance irrigation accuracy, reduce labor requirements, and improve overall farm management efficiency. Their findings indicate that automation not only minimizes operational errors but also contributes to more consistent and effective irrigation practices.

Moreover, smart irrigation systems contribute to environmental sustainability by minimizing excessive water consumption and reducing pressure on freshwater resources. Efficient water management helps prevent waterlogging, soil degradation, and nutrient leaching, which are common issues in traditional irrigation systems. In addition, reduced water usage contributes to energy savings in pumping and distribution processes. These environmental benefits make smart irrigation an important component of sustainable agricultural development. Furthermore, the adoption of such systems supports climate-resilient farming practices in areas affected by water scarcity (Idier et al., 2024).

Despite their benefits, the implementation of smart irrigation systems still faces several challenges. High installation and maintenance costs remain a major barrier, especially for smallholder farmers in developing regions. In addition, limited access to reliable internet connectivity and technological infrastructure reduces system effectiveness in rural areas. Farmers may also face difficulties in understanding and operating advanced irrigation technologies due to low digital literacy levels. These challenges hinder the widespread adoption of smart irrigation systems and limit their potential impact on agricultural efficiency. Addressing these constraints is essential for maximizing their benefits in farming systems.

Overall, the findings indicate that smart irrigation systems play a vital role in improving water use efficiency and crop production efficiency. Their ability to integrate real-time monitoring, automation, and data-driven decision-making makes them a key innovation in modern agriculture. However, to fully realize their potential, it is necessary to overcome economic, technical, and infrastructural barriers through policy support, training programs, and technological development initiatives.

2. The Impact of IoT and Artificial Intelligence on Irrigation Management Systems

The integration of Internet of Things (IoT) and artificial intelligence (AI) has significantly transformed irrigation management systems into more intelligent and data-driven agricultural solutions. IoT-based irrigation systems utilize interconnected sensors to continuously collect real-time data on soil moisture, temperature, humidity, and environmental conditions. This real-time data allows for more accurate assessment of crop water needs and improves irrigation scheduling decisions. As a result, water distribution becomes more efficient and aligned with actual plant requirements. The application of IoT in irrigation systems has been widely recognized as a key innovation in improving agricultural water management efficiency (Abu et al., 2022; Talavera et al., 2017).



Furthermore, AI enhances irrigation systems by enabling predictive analysis and intelligent decision-making based on large datasets collected from IoT devices. AI algorithms can analyze historical and real-time data to predict crop water requirements under different environmental conditions. This allows farmers to anticipate irrigation needs more accurately and reduce the risk of both over-irrigation and under-irrigation. In addition, AI-based systems can automatically adjust irrigation schedules based on weather forecasts and soil conditions. This contributes to more precise water management and improved crop productivity. These findings are supported by Liakos et al. (2018), who emphasize the role of AI in agricultural optimization.

Moreover, the combination of IoT and AI creates a fully integrated smart irrigation system that enhances automation and operational efficiency. IoT sensors provide continuous data streams, while AI systems process this information to generate actionable irrigation decisions. This integration reduces the need for manual monitoring and allows irrigation systems to operate autonomously. As a result, farmers can manage irrigation more efficiently even across large-scale farming areas. This technological synergy improves both productivity and resource conservation in agricultural systems (Kamilaris & Prenafeta-Boldú, 2018).

In addition, IoT and AI-based irrigation systems contribute to significant improvements in crop production efficiency. By ensuring that water is supplied at the right time and in the right amount, these technologies help maintain optimal soil moisture conditions for plant growth. This leads to healthier crops, improved yield consistency, and reduced crop losses caused by water stress. Furthermore, precise irrigation management reduces input waste, particularly water and energy consumption. These improvements directly enhance agricultural productivity while supporting sustainability goals (Singh, 2024).

From an environmental perspective, IoT and AI technologies also play a crucial role in promoting sustainable water resource management. Efficient irrigation reduces excessive water extraction from natural sources, helping to preserve groundwater levels and ecosystem balance. In addition, optimized irrigation reduces nutrient runoff and soil degradation, which are common issues in conventional irrigation systems. These environmental benefits highlight the importance of digital technologies in supporting sustainable agriculture. Therefore, IoT and AI integration contributes not only to productivity but also to long-term environmental protection (Idier et al., 2024).

However, the adoption of IoT and AI-based irrigation systems is still constrained by several challenges. High costs of installation, maintenance, and technological infrastructure remain significant barriers, particularly for small-scale farmers. Limited access to stable internet connectivity in rural areas also affects system performance and reliability. In addition, a lack of technical knowledge and digital literacy reduces farmers' ability to effectively operate and maintain these systems. These limitations hinder the widespread adoption of advanced irrigation technologies in agriculture.

Overall, the findings indicate that IoT and artificial intelligence play a crucial role in transforming irrigation systems into smart, efficient, and sustainable agricultural solutions. Their ability to provide real-time monitoring, predictive analytics, and automation significantly improves irrigation performance and crop productivity. However, addressing economic, technical, and infrastructural barriers is essential to ensure broader adoption and maximize their benefits in modern agricultural systems.



3. Integration of Advanced Irrigation Technologies and Sustainable Agricultural Water Management

The integration of advanced irrigation technologies has become a key approach in improving agricultural water management efficiency and supporting sustainable crop production systems. Combining smart irrigation systems, Internet of Things (IoT), artificial intelligence (AI), and data analytics creates a more comprehensive and interconnected irrigation management framework. This integrated system allows real-time data collection, processing, and automated decision-making to optimize water distribution in agricultural fields. As a result, irrigation practices become more adaptive to environmental conditions and crop requirements. This technological integration is increasingly recognized as an effective strategy for improving agricultural efficiency and sustainability (Wolfert et al., 2017; Klerkx et al., 2019).

Furthermore, integrated irrigation technologies enhance precision in water application by combining multiple data sources such as soil sensors, weather forecasts, and crop growth models. This integration enables more accurate irrigation scheduling based on real-time and predictive information. Farmers can adjust irrigation strategies dynamically according to changing environmental conditions. This reduces water wastage while ensuring that crops receive optimal water supply throughout their growth cycle. Consequently, crop productivity improves due to better water availability and management efficiency (Talavera et al., 2017; Liakos et al., 2018).

In addition, technology integration supports higher operational efficiency in agricultural irrigation systems by reducing dependency on manual monitoring and decision-making. Automated systems supported by AI can process large volumes of data from IoT devices and generate precise irrigation commands. This reduces human error and increases consistency in irrigation practices across large agricultural areas. Moreover, integrated systems allow centralized monitoring, enabling farmers to manage multiple fields simultaneously. This improves scalability and overall farm management efficiency (Kamilaris & Prenafeta-Boldú, 2018).

Moreover, integrated irrigation technologies contribute significantly to environmental sustainability by optimizing water usage and reducing resource waste. Efficient irrigation systems help minimize excessive groundwater extraction and reduce the risk of soil degradation caused by over-irrigation. In addition, better water management reduces energy consumption used in water pumping and distribution processes. These environmental benefits support long-term agricultural sustainability and ecosystem conservation. Therefore, technology integration plays a crucial role in balancing productivity and environmental protection in modern agriculture (Singh, 2024; Idier et al., 2024).

Despite these advantages, the implementation of integrated irrigation systems still faces several limitations. High investment costs for advanced technologies, system compatibility issues, and limited infrastructure remain major challenges in many agricultural regions. In addition, farmers often require advanced technical skills to operate and maintain integrated systems effectively. Without adequate training and support, the effectiveness of these technologies may not be fully realized. These barriers highlight the need for stronger institutional support and capacity-building programs to support technology adoption in agriculture (Carolan, 2020; Rotz et al., 2019).

Overall, the findings indicate that the integration of advanced irrigation technologies significantly improves crop production efficiency and water resource management. By combining IoT, AI, and smart irrigation systems, agriculture can achieve higher productivity while maintaining environmental sustainability. However, successful implementation depends on addressing economic, technical, and infrastructural challenges. Therefore, future development should focus on improving



system accessibility, affordability, and farmer digital literacy to maximize the benefits of integrated irrigation technologies.

Overall, the integration of multiple technologies is essential for achieving sustainable agricultural development (Wolfert et al. 2017). It improves productivity, efficiency, and environmental sustainability simultaneously (Pretty et al. 2018). However, successful implementation requires overcoming technical, economic, and institutional challenges (Klerkx et al. 2019). Future developments should focus on enhancing system integration and accessibility (Rotz et al. 2019). This will ensure that technological innovations can be applied effectively across different agricultural contexts (Carolan 2020). These conclusions reinforce the critical role of technology integration in sustainable agriculture (Tilman et al. 2011).

DISCUSSION

This discussion is guided by a conceptual framework that positions applied irrigation innovations as key drivers of crop production efficiency through improved water management. The framework assumes that technological innovations, including smart irrigation systems, sensor-based technologies, Internet of Things (IoT) applications, automation, and artificial intelligence (AI), enhance the accuracy and efficiency of irrigation practices by providing real-time monitoring, predictive analysis, and automated decision-making. Improved irrigation management subsequently increases resource-use efficiency by reducing water losses, optimizing energy and labor inputs, and improving nutrient utilization. These improvements ultimately contribute to higher crop productivity, greater production efficiency, and enhanced agricultural sustainability. Therefore, the relationship between irrigation innovation and crop production efficiency can be understood as a sequential process in which technological advancement improves water management, leading to better agricultural outcomes.

The findings of this study confirm that applied innovations in irrigation systems play a crucial role in improving crop production efficiency through better water management practices. The results are consistent with previous studies showing that smart irrigation technologies significantly enhance water use efficiency and crop productivity by enabling precise irrigation scheduling (Lee et al., 2021). The use of sensor-based systems and real-time monitoring allows farmers to adjust water application according to actual crop needs, reducing unnecessary water usage and improving overall agricultural performance. This supports the argument that technological innovation is essential for addressing water scarcity challenges in modern agriculture (Sharma, 2023). Therefore, smart irrigation systems can be considered a key component of efficient and sustainable agricultural production systems (Singh, 2024).

In addition, the integration of IoT and artificial intelligence has been shown to significantly improve irrigation decision-making processes. IoT devices provide continuous real-time data on soil and environmental conditions, enabling more accurate irrigation control (Abu et al., 2022). This finding aligns with previous research emphasizing the importance of real-time monitoring in optimizing agricultural water use efficiency (Talavera et al., 2017). Furthermore, AI-based systems enhance predictive capabilities by analyzing environmental and crop data to determine optimal irrigation timing and quantity (Liakos et al., 2018). This supports the hypothesis that combining IoT and AI leads to more intelligent and efficient irrigation management systems (Kamilaris & Prenafeta-Boldú, 2018).

The results also indicate that integrating multiple irrigation technologies provides greater benefits compared to using individual technologies separately. The combination of smart irrigation, IoT, and AI creates a more comprehensive system that improves data collection, analysis, and automated decision-making processes (Wolfert et al., 2017). This finding extends previous studies that mainly



focused on single irrigation technologies without considering their combined effects (Idier et al., 2024). Integrated systems allow more precise water management, resulting in improved crop productivity and reduced environmental impact. In accordance with the proposed framework, technological integration strengthens the link between irrigation management efficiency and crop production outcomes by creating a more adaptive and responsive agricultural system. This suggests that technological integration is a key factor in achieving sustainable agricultural water management (Klerkx et al., 2019).

However, the study also identifies several challenges that limit the adoption of advanced irrigation technologies. High installation and operational costs remain a major barrier, particularly for smallholder farmers in developing regions (Rotz et al., 2019). This finding is consistent with previous studies highlighting economic constraints as a major obstacle to agricultural technology adoption (Carolan, 2020). In addition, limited digital literacy and technical knowledge reduce farmers' ability to effectively operate advanced irrigation systems (Lee et al., 2021). Infrastructure limitations, such as poor internet connectivity, further hinder the implementation of IoT and AI-based irrigation systems in rural areas (Klerkx et al., 2019). These barriers indicate that the effectiveness of irrigation innovations is influenced not only by technological capabilities but also by socio-economic and institutional factors that affect technology adoption and utilization.

From a broader perspective, the findings highlight the importance of policy support and institutional involvement in promoting irrigation technology adoption. Government intervention can facilitate infrastructure development, provide financial support, and encourage technology adoption among farmers (Raj & Prahadeeswaran, 2025). In addition, training and education programs are necessary to improve farmers' technical skills and digital literacy (Carolan, 2020). This aligns with previous research emphasizing that institutional support plays a critical role in agricultural innovation diffusion (Padhiary et al., 2025). Furthermore, collaboration between stakeholders such as governments, researchers, and the private sector can accelerate the implementation of smart irrigation systems (Klerkx et al., 2019). Within the conceptual framework, these institutional factors act as enabling conditions that facilitate the successful adoption and effectiveness of irrigation innovations.

Finally, this study provides important implications for future research and agricultural practice. Future studies should explore more cost-effective and scalable irrigation technologies that can be adopted by smallholder farmers (Rotz et al., 2019). There is also a need to examine the long-term environmental and socio-economic impacts of integrated irrigation systems in different agricultural contexts (Idier et al., 2024). In addition, future research should focus on improving system accessibility and user-friendliness to increase adoption rates. Strengthening policy frameworks and institutional support will also be essential to ensure the successful implementation of advanced irrigation innovations (Tilman et al., 2011). Future investigations may also validate and expand the proposed conceptual framework by examining the direct and indirect relationships among irrigation innovations, resource-use efficiency, technology adoption factors, and crop production efficiency across different agricultural settings. These directions will help enhance the effectiveness and sustainability of irrigation systems in modern agriculture.

CONCLUSIONS

This study concludes that applied innovations in irrigation systems play a significant role in improving crop production efficiency through enhanced water use management and precision irrigation practices. Technologies such as smart irrigation systems, IoT, and artificial intelligence contribute to more efficient water distribution, real-time monitoring, and data-driven decision-making in agricultural



activities. These innovations help reduce water waste, improve crop productivity, and support more sustainable farming practices.

In addition, the integration of multiple irrigation technologies provides greater benefits compared to standalone systems, as it enables more comprehensive and automated irrigation management. However, the adoption of these technologies is still constrained by several challenges, including high costs, limited infrastructure, and low digital literacy among farmers.

Therefore, strong policy support, improved technological infrastructure, and capacity-building programs are needed to accelerate the adoption of advanced irrigation systems. Overall, applied irrigation innovations are essential for achieving sustainable agricultural water management, and future research should focus on developing more affordable, scalable, and inclusive solutions to support wider implementation across different agricultural contexts.

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