

# Smart Irrigation Technologies for Climate-Resilient Agriculture: Trends, Challenges, and Future Research Directions

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**Abstract** - Climate change and water scarcity are placing increasing demands on agricultural systems, and there is a need for better irrigation methods. While conventional irrigation methods are still crucial in many areas, they are often limited by water wastage, inaccurate timing and lack of flexibility in response to weather variability. This review examines the rise of smart irrigation for improving climate resilience in agriculture. It examines the impact of climate change on agriculture and water resources, describes key irrigation-related issues, including drought, water stress, and low productivity, and considers traditional irrigation and smart irrigation systems, including Internet of Things (IoT)-based systems, soil moisture sensing, artificial intelligence (AI)-based scheduling, automation, and remote sensing. The reported resilience and the potential benefits of smart irrigation are also explored in terms of water-use efficiency, crop yield, energy resilience and the key challenges are identified with respect to cost, infrastructure, interoperability and implementation. The literature indicates that smart irrigation has great potential for improving agricultural water management but its long-term success depends on its cost, implementation and integrated and tested systems.

**Keywords** - smart irrigation, climate-resilient agriculture, IoT, sustainable water management, water scarcity.

## I. INTRODUCTION

The agricultural sector is highly vulnerable to climate change because growth of crops, water supply, and agricultural operations all rely on the environment. Recent studies indicate that the agricultural production is becoming more uncertain due to the growing variability in climate, rising temperatures, and the number of extreme weather events. [1], [2]. The changes not only lead to a decrease in the stability of crop yields in climate-sensitive regions but also impose additional demands on the already limited land and water resources. As a result, the climate-resilient irrigation is no longer about providing water, but has now become the leading front in ensuring agricultural productivity, adaptation and sustainability in the new agricultural landscape [3].

Climate change impacts on water resources are one of the most severe impacts. The change in rainfall patterns and rising temperature reduce water availability, and lead to complex irrigation management [3], [4]. The situation is even more disastrous when irrigation is inappropriately timed or when water is not used efficiently, as a result of which the yield of crops decreases and resources are wasted [5]. This implies that the new agricultural systems should not only identify a good source of water, but they should also provide the water at the appropriate time and quantity. That is, it is not only the

amount of water, but the efficiency of its utilization in various places and crop development phases.

In this regard, the demand for climate-proof water management practices becomes critical to improve agricultural production. With the increased and more severe occurrence of extreme weather phenomena like droughts and floods, farmers need to implement irrigation methods that are more reliable to access water and reduce wastage and enhance efficiency. Different methods such as drip irrigation, sprinkler irrigation, center pivot irrigation, hydrogels, soil and water evaluation instruments have been listed as viable solutions to address the problem of water management in agriculture [2]. The practices do not only lead to increased water-use efficiency but also aid the livelihood of the farmers especially the small scale farmers who are most susceptible to climate variability. With that, crop management practices should be employed to complement strategies for irrigation, such as switching to less water-intensive crops that will prove more resilient in the changing climate. Overall, these strategies highlight the need for better water management in order to create a more sustainable agricultural system.

To eliminate these challenges, smart irrigation has received considerable concern as a remedy to climate-resilient agriculture. According to the recent research, there has been a trend towards more sophisticated systems that employ sensors, Internet of Things (IoT) technologies, remote monitoring, and machine learning to enhance irrigation decisions [6]. This is an important shift in irrigation as it changes the irrigation process from being time-controlled to data-controlled. Smart irrigation systems do not irrigate the crops at designated times, but automatically regulate the water flow according to the current environmental factors, crop requirements and even weather predictions.

Conventional irrigation systems including surface and sprinkler irrigation are still extensively employed but tend to be unresponsive to the real field conditions, resulting in inefficiency and waste of water [7], [8]. Conversely, the current data-driven methods also integrate IoT devices, sensors, artificial intelligence, and remote monitoring to enable irrigation to be more precise and flexible [9]. Nevertheless, regardless of these developments, there are still challenges. The inconsistent performance of many systems, their inability to be validated in the real world, and cost, infrastructure, and scalability barriers continue to exist [10], [11]. This is why this paper will review and critically examine smart irrigation technologies as a solution to climate-resilient

agriculture by examining the current solutions, challenges and future research opportunities.

## II. METHODOLOGY

This paper adopts a critical review to analyse the development of smart irrigation technologies for climate-resilient agriculture. The literature is categorised into analytical themes in line with the focus of this paper; these include technological developments such as IoT, artificial intelligence and remote sensing; challenges of adopting smart irrigation such as cost, infrastructure and interoperability; and research opportunities. This enables a systematic examination of the nature of smart irrigation, the barriers in the adoption of smart irrigation, and the potential to enhance smart irrigation development by aggregating findings from multiple studies rather than comparing individual studies.

The studies reviewed in this paper are analyzed comparatively, including: general descriptions, smart irrigation system design, smart irrigation implementation-based studies, and reviews on smart irrigation sensing, machine learning, and precision agriculture. This sets the directions for overlap, gaps and research opportunities.

While the paper is thematically organised, it also has elements of critical synthesis. The literature is not regarded as a set of independent studies, but as an evidence base that can be compared in terms of technical, practical and deployment readiness. This is to not just describe the studies, but to understand the field of study, and assess the suitability of the technologies within a specific context.

The selection of the literature was based on a structured but non-systematic search process that prioritizes synthesis. The literature review involved finding relevant literature using academic databases, mainly ScienceDirect and Google Scholar, which cover a wide range of peer reviewed literature in the field of agriculture, engineering and information technology. These were deemed adequate sources to aid the thematic synthesis and comparative analysis that have been used in this study.

Keyword combinations included smart irrigation, climate-resilient farming, IoT irrigation, soil moisture monitoring, artificial intelligence, machine learning, irrigation management, precision agriculture, remote sensing, and water management. Search operators (AND, OR) were applied to narrow down the search.

The review was mainly limited to literature published in the recent years (2016-2026) to understand current technological advances, although some earlier foundational literature was included selectively in order to facilitate conceptualisation.

The selection of the studies was undertaken through a screened process in stages in accordance with the review themes. First, studies were selected based on the titles and abstracts for relevance to smart irrigation and climate-resilient agriculture. Thereafter, full-text assessment was done to find out whether the studies were of any significance to the identified thematic categories.

The inclusion criteria were peer-reviewed publications, conference papers and review articles which discussed smart irrigation technologies, system design, implementation or evaluation of the system in the context of agriculture. The studies were classified based on the study of the technological

development, system design and architecture, agronomic feasibility or implementation.

The exclusion criteria were studies that were not specific to irrigation in agriculture (e.g. non-agricultural IoT applications), and other non-scholarly sources. Articles that only covered environmental monitoring and not directly related to irrigation were also not included.

The selected studies were categorised based on the proposed thematic scheme to conform to the critical thematic synthesis performed in this review.

## III. CLIMATE CHANGE AND IRRIGATION CHALLENGES

### Drought and Water Scarcity

Drought and water shortage are no longer the sole agricultural issues but they are structural problems that are redefining irrigation needs. Studies on climate-resilient irrigation suggest that rising temperature, reduction in rainfall and growing water deficit are having a significant impact in irrigation systems in most cropping systems [1], [3]. This indicates that irrigation is no longer a marginal process that is confined to dry seasons but it has become a core process of stabilizing crop production even where there is climatic stress. Irrigation is becoming more crucial and complicated in areas where water sensitivity is already a significant issue.

However, the literature also highlights a crucial point of distinction, it is not only the fact that there is the lack of water that leads to the problem of water scarcity, but also the fact that water is not managed efficiently. Water losses can be caused by poor application timing, overwatering, poor distribution, insufficient monitoring, and failure to adjust to varying field conditions [2], [5]. This is a major difference, implying that climate-resilient irrigation methods could not be solely based on increased water infrastructure. They should also enhance decision-making and implementation which means that it is both a hydrological and managerial issue.

The literature further shows that the dual challenge is exacerbated by climate change, which increases uncertainty in water demand. The increased rates of evapotranspiration, changes in rainfall distribution and increased climatic variability making the traditional irrigation assumptions less effective [3], [4]. The fixed irrigation schedules are less predictable and reliable as they rely on anticipated trends and not the actual crop and soil condition. This drawback has led to the increased focus on accuracy and flexibility as crucial demands in contemporary irrigation studies.

### Agricultural Productivity and Water Stress

Recurring theme in the literature is the impact of water stress on the agricultural productivity. Water stress affects crop growth, yield and stability of production particularly when irrigation timing is out of synchronization with crop demand. The scheduling-based researches demonstrate that the success of irrigation is not only related to the quantity of water that is used, but it is also associated with the timing and location of water application [5]. This makes irrigation linked with crop response rather than a stand-alone, hydraulic process.

The concept of climate-resilient agriculture helps to reinforce this point of view and underline the idea that the aim of productivity needs to be aligned with the demands of adaptation. Irrigation systems are anticipated to not only sustain yield but also increase climate variability resilience

and resource efficiency [3]. This development forms the basis of intelligent irrigation technologies which endeavor to control water with more precision in changing environmental conditions.

A key implication of the literature is that irrigation can no longer be regarded as only a technical delivery system. It is increasingly integrated into a wider resilience context in which water availability, climatic conditions, crop physiology, and management decisions interact. It is on this basis that most of the recent research has defined irrigation as a decision-support problem instead of just an engineering one [5], [12]. The value of decision accuracy is more important as the variability of climatic conditions rises. Smart irrigation is an attempt in this direction to reduce the uncertainty in terms of better information, speed of response and higher adaptability.

#### IV. CONVENTIONAL IRRIGATION SYSTEMS

##### Surface irrigation

Surface irrigation is popular because it is easy to use, accessible and has a low initial cost. But it is also one of the most inefficient methods of irrigation, particularly in a water-scarce environment with variable climate where more precision is required [7]. Runoff, deep percolation, and poor water distribution across the field limit the efficiency of the method and make it challenging to align water supply with crop water demand. Surface irrigation is also very sensitive to field conditions, topography and user skills. This makes it difficult to predict how it will perform in different regions [7], [8]. Although this may not be a major issue under steady conditions, it can be a concern under climate variability as the system is difficult to adjust to sudden changes, such as water shortage and climatic variability. Therefore, the problem is not that surface irrigation is old-fashioned, but that it is generally not designed to be dynamic and respond to real-time data.

##### Sprinkler irrigation

Sprinkler irrigation is more adaptable than surface irrigation, and is frequently used where water must be delivered uniformly across a larger area of cropland [7]. Sprinkler irrigation systems can offer improved coverage and reduced some of the field losses that occur with surface irrigation systems. But they can also be adversely affected by environmental conditions including wind, evaporation, and pressure fluctuations, which can lead to lower efficiency in changing climate [7], [8]. Therefore, while sprinkler irrigation can be more efficient than surface conventional systems in some cases, it is not as responsive as smart irrigation systems. Therefore, sprinkler irrigation is a semi-advanced system in the irrigation hierarchy. It offers better mechanical water distribution than simple conventional irrigation systems, but may not be better in responsiveness and decision-making. Even with fixed schedules or manual control, it can still be over-irrigation or under-irrigation that does not consider the water needs of the crop. It is also constrained, not just by the efficiency of the water distribution system, but also scheduling and monitoring [8].

##### Conventional Irrigation disadvantages.

The primary disadvantage of conventional irrigation, as reported in the literature, is not the lack of water delivery, but the lack of responsive, adaptive and real-time irrigation that is required for climate-smart agriculture. In general reviews,

traditional systems are often reported to be not linked to field conditions, and irrigation is therefore not time-responsive and is carried out on a routine basis rather than based on the needs of the crop and soil [8]. This is the problem that smart irrigation technologies seek to solve.

Another issue with conventional systems is that they can be an over-simplified square field. They are generally not designed to address the spatial variability of the fields in terms of soil moisture, crop condition and microclimate stress [9]. As a consequence, they can be adequate in the mean, but can still cause local inefficiencies and variability in the crop [7], [8]. This is unsustainable in the context of climate change and water scarcity. Hence, smart irrigation is not only a different technology but even a different paradigm, from water supply to water management.

#### V. SMART IRRIGATION TECHNOLOGIES

##### IoT-based irrigation systems

Among the key innovations in irrigation is the evolution from stand-alone irrigation devices to networked systems based on IoT (Internet of Things). Such systems integrate sensors, controllers, communication and user interfaces to offer real-time irrigation decisions based on data. We know that IoT systems enable remote and real-time environmental monitoring and thus prompt decision making [9]. This will make irrigation no longer a periodic process that is done in the field but an automated process.

IoT is not just about connectivity, but also integration. Remote sensing, communication to cloud, awareness of weather conditions, and the use of solar power suggest that smart irrigation systems are evolving to become a holistic infrastructure rather than a set of stand-alone components [13], [14]. Research also suggests that system maturity is reflected in the evolution of multi-layered architecture: sensing, communication, processing and application layers [15].

The value of this design trend in relation to resilience is linked to the increase of the range of heat distribution to distributed intelligence through extension of irrigation. Data can be collected and transferred in real time, using wireless networks, processed on-site or in cloud and the results sent to assist in making or influencing irrigation decisions in near real-time [9], [15]. This presents a chance of more responsive irrigation with varying conditions. However, it is not connectivity that introduces the value of IoT. It is dependent on whether the system that is connected actually results to increased quality of decisions, improved level of operation and utility at the farm level.

##### Soil moisture sensor irrigation

One of the most stable grounds of smart irrigation is soil moisture sensing. Irrigation strategies aim to approach crop water demand which is why soil moisture status is a good source of information. Experimental trials demonstrate that irrigation systems controlled by soil moisture sensor-controlled irrigation systems can directly link the water supply to the field, avoiding excessive use and providing better control [16]. But irrigation control using sensors is not a complete solution. Low-cost sensor platform implementations and microcontrollers demonstrate that the field implementation is feasible but also that there is a weakness of the sensor calibration, communication and long-term

reliability [17]. This implies that while soil moisture sensing is important, it requires integration with data analytics, control and maintenance. Further, the success of soil moisture sensors depends on the depth, location, calibration and interpretation. Therefore, it's not about the effectiveness of soil moisture measurement, but its practical and feasible use in the field [16], [17].

#### AI-based irrigation scheduling

Artificial intelligence (AI) is also a rapidly-growing field in smart irrigation management, as irrigation scheduling is a form of prediction and decision-making. Machine-learning irrigation scheduling systems can consider multiple factors including weather, evapotranspiration, soil moisture, crop growth and history [12]. Such techniques are particularly valuable in capturing complex and non-linear relationships that other techniques may miss. The literature has shown a shift in irrigation from reactive to predictive. AI can help with not only irrigation scheduling, but also in resource management and climate adaptation [18], [19]. However, much existing work is either based on limited or controlled data sets and more work is required to test AI irrigation systems under different conditions before they can be applied universally [10].

The further comparison of smart irrigation technologies indicates that there is a crucial difference in maturity. The sensor-based systems are usually more workable and more commonly deployable as they directly measure the situation in the field. The AI-based systems, on the other hand, are more flexible and predictive, but also require better data, model validation and computational integration. This suggests AI is a promising approach, but not yet a worldwide, in-field replacement of simpler systems.

The role of AI in this area is thus not the replacement of all the existing irrigation logic but the extension. Pattern recognition, water demand prediction, uncertainty optimization, and dynamic adaptation to the changing conditions of the fields may be facilitated with the help of AI [10], [12], [18], [19]. On the other hand, the literature suggests that AI does not decrease the demand for agronomic expertise. Instead, it requires more data, objective and interpretation.

#### Automated irrigation systems

Automation is often cited as a core element of smart irrigation; But it is better understood as a control system that links information to irrigation. In precision agriculture, research suggests the importance of using sensors, control and communication technologies to deliver real-time, site-specific irrigation processes [20]. In such applications, automation is more than merely a means to activate systems, it is part of an information-based system. Automated irrigation systems are not all equally effective. Although systems without sensing and decision-making technologies can boost productivity, they do not necessarily increase irrigation intelligence. In contrast, systems with sensors, prediction and control are more adaptable to the field conditions [20]. Automation has varying degrees of functions. At the lowest level, it decreases workloads. At an intermediate level, it provides better timing, consistency and responsiveness. At the highest level, when integrated with sensor technologies and predictive models, it is an element of a dynamic system of irrigation that is more than just automation [20]. This is an important point in not

overestimating automation as being "smart." Automation does not necessarily lead to smart irrigation, it needs to be co-integrated with an analytics-based decision support system.

#### Remote Sensing

Remote sensing takes smart irrigation from point to area-based analysis. Using satellite data and geographic information systems (GIS), it allows for large-scale monitoring of crop status, vegetation status and field variability. One study recommended remote sensing as it can effectively detect large-scale anomalies such as crop stress and variability which may be unnoticed by ground sensors [21]. Remote sensing is also effective in conjunction with machine learning and IoT as a fused monitoring system. According to framework studies, it is possible to combine satellite data, IoT sensors, and predictive models to enhance crop monitoring, irrigation recommendation, and climate stress detection [22]. This suggests that there is a shift in research towards data fusion where irrigation is not based on one source of data but integrates field level and landscape level data.

Remote sensing is particularly useful in situations where the cost and effort of dense field measurements are difficult, expensive or impossible. It can provide a greater global spatial view, risk assessment and improved understanding of sensor data [21], [22]. However, the literature also hints that remote sensing is best used in combination with other ground observations and not as a replacement. It has scale as its key advantage; it has space monitoring that can be not enough to capture the operating details as needed in instantaneous irrigation control. Therefore the shift towards integration and not substitution.

## VI. BENEFITS OF SMART IRRIGATION

### Water efficiency

The most frequently mentioned advantage of smart irrigation is improved water-use efficiency. They increase irrigation accuracy, minimise water wastage and improve irrigation management to better match crop needs [23]. This is crucial for water scarcity. Being water efficient is not only important for water saving, but also for sustainability, resilience and profitability in water scarce areas. It is therefore not just a measure of performance, but a critical element of the importance of smart irrigation for climate smart agriculture [23].

### Increased crop yield

Crop yield is also a key driver of the benefits of smart irrigation, although this varies with crop characteristics, climate and the complexity of the system. Research shows that enhanced monitoring and forecasting can increase crop stability and yield, especially when irrigation practices are based on field conditions [24]. Smart irrigation does not necessarily maximise yield, but can improve yield stability, increased resilience to irrigation errors and increased efficiency under changing conditions. It is especially important for climate-sensitive agriculture [24].

### Reduced energy consumption

Besides water savings, smart irrigation systems can also enhance energy efficiency in irrigation systems by minimizing wasted pumping and water delivery processes [25]. This is especially important for pressurized and motorized irrigation systems. Energy efficiency is more important when coupled

with renewable energy sources such as solar irrigation systems [13], [14], [24]. In such irrigation systems, water, energy and climate sustainability is increasingly recognised as part of sustainable irrigation [25].

#### Climate resilience

Smart irrigation plays a role in climate resilience by improving the adaptability, responsiveness and information-based nature of water management in agriculture. Studies point out that resilience is not only related to infrastructure but also to information and decision-making capabilities [11]. At a systems level, larger smart water audits support this view by proposing that the future of irrigation should be the use of integrated soil-water-crop management with the support of smart monitoring and adaptive decision-making tools [26]. This is, arguably, the most important conceptual benefit as it considers the broader significance of smart irrigation. Smart irrigation builds resilience, by making it more resilient to uncertainty, more resourceful in adapting to the environment and more informative for resource management [11], [26]. In this regard, climate resilience is not an additional product that is added to irrigation, it is becoming part of the goal of irrigation in modern agricultural systems.

### VII. CHALLENGES AND LIMITATIONS

Even with the promising outlook for smart irrigation systems as reported in the literature, there are many challenges that affect their uptake and effectiveness. A major issue is the cost. The requirement for sensors, controllers, communication devices and other infrastructure results in a significant up-front cost, especially for smallholder farmers [11]. This means that although technical efficiency is vital, economic efficiency and affordability is the key to adopting smart irrigation. The other significant problem is the difference between the prototype performance and the actual implementation. Review studies often report about technically impressive systems, yet those systems are often tested in constrained environments, not in the context of long-term changes of a real farm [10], [20]. This leads to a paradox on the literature, the field is technologically ambitious but practical deployment has not been even. Digital skills, implementation limitations, infrastructure constraints, and power or connectivity constraints all diminish the success of implementation [11], [26].

A third weakness is interoperability. The use of smart irrigation is increasingly based on several subsystems, sensors, IoT, analytics tools, cloud or edge, and user interfaces, however, literature on standardized architectures that can be low-cost, reliable and reproducible across contexts, is still lacking [15], [22]. This is one of the research and deployment gaps.

There is also a barrier of knowledge and ability evident in the literature. Although systems might technically be available, these systems might create challenges concerning training, trust, interpretation of recommendations, and long-term maintenance [10], [11]. Thus, smart irrigation should not just be considered a technological problem but also a problem of integration and implementation. Not just effective technologies but practical, accessible, manageable and relevant technologies are needed.

Lastly, it has a scale issue. The same technology can be effective in a controlled experiment, pilot plot, or even in a particular crop system and fail in many different agroecological and socioeconomic situations. That is why the literature continuously stresses the field validation, cross-context testing, and implementation realism [10], [11], [26]. Although smart irrigation has great potential, it is still in its infancy with regards to widespread adoption.

### VIII. FUTURE RESEARCH DIRECTIONS

A number of priorities should be considered for future development of smart irrigation. To start with, the integration of AI must be more rigorous and should be validated in the field with more intensive cross-crop, cross-dataset, and cross-environmental comparisons [10], [12]. The literature is increasingly demonstrating the predictive capacity of AI, but further research is required to evaluate the accuracy of AI models but also the efficiency, transferability and applicability of the AI model to real-world use.

Second, big data agriculture needs to become more than a term to create a framework to allow the integration of diverse data into irrigation decision systems [14], [20], [22]. This involves the scheme of integrating the weather information, soil moisture information, crop status information, satellite data, and historical information into coherent decision support systems to be employed by the farmers and managers and not just the researchers.

Third, the adaptability of irrigation must be more system-oriented. Smart irrigation should become more integrated into a management system where the technologies to measure soil moisture, weather, remote sensing and models for predictions are combined [23], [26]. The sector is transitioning from individual technologies to systems and future research will be of most benefit if systems are technically but also practically possible.

Other areas that require further focus include affordability, modular system design, and interoperability. The impact on long-term results may be limited by research that provides highly accurate systems, but does not account for deployment conditions. As such, future research should not only consider the measurement and control of irrigation systems, but also the cost and financing models, cost-effective system solutions, maintenance requirements, user-friendly design and institutional support [10], [11]. The greatest future problem is therefore not the creation of one additional isolated irrigation device, but the creation of systems that are precise, interoperative, cheap and robust enough to be utilized in real-world agricultural systems. It is here that the greatest strides will be made.

### IX. CONCLUSION

The use of smart irrigation technologies has become even more relevant in the face of increasing climate change, water scarcity and food security challenges. This review demonstrates a shift from traditional irrigation systems to integrated, data-centred systems that integrate sensing, automation, artificial intelligence and decision support. Irrigation systems are becoming more responsive and efficient by adjusting to the variable environmental and crop conditions, rather than being strictly scheduled.

However, the literature also highlights that the evolution of smart irrigation comes with challenges. Although they can potentially improve water-use efficiency, crop yield, and climate adaptation, their use is limited by the costs, infrastructure and interoperability, and the transition from research to practical application. These challenges suggest that technological development alone is insufficient without effective, affordable and accessible technologies.

This review shows that irrigation is no more just water supply, but involves a soil, crop, environment and decision-making support system. Smart irrigation technologies are important in linking these components for a more integrated and responsive approach. But this also adds to the complexity, which remains a barrier to adoption.

Future progress in smart irrigation will depend on shifting from prototype-based development toward field-ready systems that are affordable, interoperable, and validated across diverse agricultural contexts. Consideration should be given to not only the technological accuracy but also the practicality, scalability and sustainability of the technologies.

To conclude, smart irrigation technologies have great potential for climate-resilient agriculture. They have a future beyond water savings to enhance the adaptability, responsiveness and productivity of agricultural systems under changing and uncertain climates.

## REFERENCES

- [1] S. Turaeva and G. Sultanova, "Climate change impact on agriculture and water resources: Uzbekistan," in *SDGs in the Asia and Pacific Region*, pp. 249-269. Cham: Springer International Publishing, 2024.
- [2] S. Chouhan, S. Kumari, R. Kumar, and P. L. Chaudhary, "Climate resilient water management for sustainable agriculture," *International Journal of Environment and Climate Change*, vol. 13, no. 7, pp. 411-426, 2023.
- [3] J. Singh, A. Kumar, N. Karn, R. Kumar, A. Parnian, M. Mahbod, and M. A. E. AbdelRahman, "Climate-resilient irrigation: Adapting to a changing world," in *Irrigation Management: Strategies, Sustainability and Agricultural Advancements*. New York, NY, USA: Nova Science Publishers, pp. 1-36, 2025.
- [4] S. Saha, "Economic Strategies for Climate-Resilient Agriculture: Ensuring Sustainability in a Changing Climate," *Demographic Research and Social Development Reviews*, vol. 1, no. 1, pp. 1-6, 2024.
- [5] Z. Gu, Z. Qi, R. Burghate, S. Yuan, X. Jiao, and J. Xu, "Irrigation scheduling approaches and applications: A review," *Journal of Irrigation and Drainage Engineering*, vol. 146, no. 6, p. 04020007, 2020.
- [6] A. Irum and M. A. Hameed, "SMART IRRIGATION SYSTEM FOR CLIMATE RESILIENT AGRICULTURE: A SYTEMATIC LITERATURE REVIEW," *Gomal Journal of Agriculture and Biology*, vol. 3, no. 02, pp. 98-112, 2025.
- [7] D. Bhavsar, B. Limbasia, Y. Mori, M. I. Aglodiya, and M. Shah, "A comprehensive and systematic study in smart drip and sprinkler irrigation systems," *Smart Agricultural Technology*, vol. 5, p. 100303, 2023.
- [8] Y. Gamal, A. Soltan, L. A. Said, A. H. Madian, and A. G. Radwan, "Smart irrigation systems: Overview," *Ieee Access*, 2023.
- [9] K. Obaideen, B. A. Yousef, M. N. AlMallahi, Y. C. Tan, M. Mahmoud, H. Jaber, and M. Ramadan, "An overview of smart irrigation systems using IoT," *Energy Nexus*, vol. 7, p. 100124, 2022.
- [10] M. Belmir, W. Difallah, and A. Ghazli, "A Systematic Review of the Implementations of Artificial Intelligence and Internet of Things Solutions in Smart Irrigation Systems," *Journal of Engineering Science & Technology Review*, vol. 18, no. 3, 2025.
- [11] A. Abubakar, S. Magaji, and Y. Ismail, "Bridging The Adaptation Gap: Barriers and Opportunities for Climate-Resilient Irrigation Farming in Dutse LGA, Jigawa, Nigeria," *International Journal of Progressive Sciences and Technologies (IJPSAT)*, vol. 52, no. 2, pp. 229-241, 2025.
- [12] M. K. Saggi and S. Jain, "A survey towards decision support system on smart irrigation scheduling using machine learning approaches: Ks saggi. s. jain," *Archives of computational methods in engineering*, vol. 29, no. 6, pp. 4455-4478, 2022.
- [13] M. Mohammed and A. Derbala, "Advanced IoT-Based Remote Monitoring and Control for Smart Solar-Powered Irrigation Systems," *Journal of Sustainable Agricultural and Environmental Sciences*, vol. 3, no. 3, pp. 125-132, 2024.
- [14] B. Et-Taibi, M. R. Abid, E. M. Boufounas, A. Morchid, S. Bourhane, T. A. Hamed, and D. Benhaddou, "Enhancing water management in smart agriculture: A cloud and IoT-Based smart irrigation system," *Results in Engineering*, vol. 22, p. 102283, 2024.
- [15] A. A. Abdelmoneim, H. N. Kimaita, C. M. Al Kalaany, B. Derardja, G. Dragonetti, and R. Khadra, "IoT sensing for advanced irrigation management: A systematic review of trends, challenges, and future prospects," *Sensors*, vol. 25, no. 7, p. 2291, 2025.
- [16] M. Pramanik, M. Khanna, M. Singh, D. K. Singh, S. Sudhishri, A. Bhatia, and R. Ranjan, "Automation of soil moisture sensor-based basin irrigation system," *Smart Agricultural Technology*, vol. 2, p. 100032, 2022.
- [17] B. R. Reddy, K. Hegde, I. B. C. Reddy, and V. Sivakumar, "Smart drip irrigation system using IOT," in *Proceedings of the International Conference on Innovative Computing & Communication (ICICC)*, Apr. 2021.
- [18] S. Kaushik and K. Singh, "Ai-driven smart irrigation and resource optimization for sustainable precision agriculture," *Europe*, vol. 250, p. 70, 2025.
- [19] R. Khan and P. Sharma, "AI-Enabled Smart Irrigation for Climate-Resilient Agriculture," in *SHS Web of Conferences*, vol. 216, p. 01005. EDP Sciences, 2025.
- [20] A. Soussi, E. Zero, R. Sacile, D. Trincherro, and M. Fossa, "Smart sensors and smart data for precision agriculture: a review," *Sensors*, vol. 24, no. 8, p. 2647, 2024.
- [21] S. J. Haque, S. Hossain, and M. M. Billah, "Precision agriculture through remote sensing and GIS: Advancing sustainable farming and climate resilience," *Am. J. Smart Technol. Solut*, vol. 4, pp. 30-36, 2025.
- [22] N. Agarwal, M. D. Arif, and R. Chandra, "Machine Learning Approaches for Climate-Resilient Smart Agriculture Using Remote Sensing and IoT Technologies," *VW Applied Sciences*, vol. 8, no. 1, 2026.
- [23] S. M. Z. A. Naqvi, S. Hussain, M. Awais, M. N. Tahir, S. R. Saleem, F. A. Al-Yarimi, ... and J. Hu, "Climate-resilient water management: Leveraging IoT and AI for sustainable agriculture," *Egyptian Informatics Journal*, vol. 30, p. 100691, 2025.
- [24] N. Nurmalitasari, N. Nurchim, and R. D. Lestari, "Artificial intelligence-driven solar smart irrigation for sustainable agriculture: Trends, challenges, and SDG implications—A systematic review," *Smart Agricultural Technology*, p. 101665, 2025.
- [25] Y. Durmuş, G. Arslansoy, and T. K. Gürbüz, "Impact of smart irrigation systems and water management on climate change," in *BIO Web of Conferences*, vol. 85, p. 01057. EDP Sciences, 2024.
- [26] M. A. AbdelRahman, "Smart water for sustainable agriculture through climate resilient assessment and integrated soil water crop management," *Discover Water*, 2026.