Innovative Irrigation Solutions in Arid Climates of Iran

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ABSTRACT

Given the increasing frequency of droughts, reduced rainfall, and growing pressure on water resources, finding innovative irrigation solutions for the arid climates of Iran is essential. This paper explores modern irrigation technologies and methods, such as subsurface irrigation, smart irrigation systems, the use of soil moisture sensors, and the application of the Internet of Things (IoT) in agricultural water management. The goal is to enhance water use efficiency, reduce losses, and achieve sustainable agriculture in the dry regions of the country. The results show that the implementation of these technologies significantly reduces water consumption and increases production efficiency. These technologies can provide effective solutions to address water scarcity challenges in agriculture, particularly in the dry and semi-dry regions of Iran. Not only do they reduce water consumption, but they also improve agricultural productivity and reduce irrigation and energy costs. Implementing these systems can contribute to the sustainable management of water resources and increase agricultural outputs, ultimately leading to more sustainable agriculture.

Keywords: *Smart irrigation, arid climate, water use efficiency, sustainable agriculture, Internet of Things (IoT).*

1. *INTRODUCTION*

Iran is a country with notable climatic diversity, but a large portion of its land is covered by arid and semi-arid climates. The country's average annual precipitation is about 250 mm, whereas the global average exceeds 800 mm. On the other hand, rainfall distribution in Iran is highly uneven, with most precipitation occurring as short-term, torrential rainfall during specific seasons, which neither infiltrates the soil nor is suitable for proper storage in water resources. These conditions, combined with high evaporation rates and global warming, have led to a serious water crisis in the country [1, 2 and 3].

In recent decades, the decline in renewable water resources, the lowering of groundwater levels, increasing salinity in water and soil, and the growing competition for water resources between agricultural, industrial, and drinking sectors have created serious threats to economic development and social sustainability in Iran's dry regions. Since over 90% of the country's water consumption occurs in the agricultural sector, and at the same time, water use efficiency in many areas is below global standards, it can be concluded that the key to solving Iran's water crisis lies in revisiting and reforming the water consumption patterns in the agricultural sector [4, 5].

Traditional irrigation methods, which are still common in many areas of Iran (such as surface and flood irrigation), not only lead to significant water waste (sometimes up to 50%), but also cause soil degradation, increased salinity, and reduced crop yields. In contrast, modern irrigation technologies developed in recent decades allow for optimal and precise management of water resources. These technologies include advanced drip irrigation, subsurface irrigation, automated systems based on soil moisture and weather sensors, Internet of Things (IoT)-based remote control systems, and the use of remote sensing data and climate forecasting for better irrigation scheduling [5, 7].

The application of these technologies not only leads to reduced water consumption but also increases crop productivity, reduces production costs, decreases dependence on human labor, and enhances the agricultural system's resilience to climate change. For example, smart irrigation systems can make real-time decisions on when and how much to irrigate to ensure maximum plant uptake and minimize water waste [7].

However, the implementation of these new technologies also comes with challenges. High initial costs, lack of technical training, weak communication infrastructure in some rural areas, and the lack of awareness or resistance among some farmers to technological changes are among the barriers that have slowed the development of these systems. Therefore, success in implementing modern irrigation solutions requires a multidimensional approach, including education, government support, private sector involvement, and the design of effective incentive policies [8].

In this context, paying attention to the climatic and local characteristics of each region is of great importance. What works in one area may not yield the desired results in another. For this reason, regional studies, continuous monitoring of results, and the adaptation of technology to local conditions must be prioritized. The aim of this paper is to provide a comprehensive and analytical review of modern irrigation solutions suitable for Iran's arid climates, focusing on cutting-edge technologies, assessing water-saving potential, increasing productivity, and evaluating the feasibility of their implementation in real-world conditions in dry regions of the country. This review seeks to offer practical, locally adapted solutions that can pave the way for sustainable agricultural development in these regions.

2. MATERIALS AND METHODS

In this study, a combination of three main methods was used, including a literature review, case study analysis, and the use of field experiences in the arid regions of the country. This mixed-method approach was aimed at gaining a realistic understanding of the capabilities, limitations, and performance of modern irrigation methods in Iran's dry regions.

In the literature review phase, scientific articles, technical reports, and both domestic and international research projects were examined to identify feasible and applicable irrigation methods for these regions. Simultaneously, field studies and documented experiences from experimental farms and implemented projects, particularly in the mentioned provinces, were used as empirical references.

The modern methods explored in this research include subsurface irrigation, which reduces surface evaporation by directly delivering water to plant roots and improves irrigation efficiency; smart drip irrigation, which relies on moisture sensor data to adjust irrigation timing and amounts precisely based on the plant's needs; soil and climate sensors that monitor environmental conditions such as temperature, humidity, and light intensity, helping with optimal irrigation decision-making; Internet of Things (IoT)-based systems that enable automatic, remote control of irrigation systems through data collection and analysis; and finally, the use of saline or recycled water, which, if coupled with the use of drought-resistant plants, can partially offset the shortage of freshwater resources.

In summary, the application of these methods can be an effective step toward better water resource management in Iran's dry regions, and the core analysis and recommendations of this paper are based on these technologies and practical experiences.

3. SUBSURFACE IRRIGATION

Subsurface irrigation is an advanced irrigation method in which water is directly supplied to the soil depth and near the plant roots, instead of being sprayed on the soil surface. This method is designed to minimize evaporation and prevent water wastage, making it particularly useful in dry and semi-dry regions where water scarcity is a significant issue. In subsurface irrigation systems, pipes or strips specifically designed for this type of irrigation are placed underground. These pipes or strips can be installed at regular intervals below the surface of the soil and deliver water directly to the plant roots. As a result, the surface soil dries out, which helps prevent the growth of weeds that typically rely on the moisture of the soil surface [9, 11 and 12].

The advantages of this method, compared to traditional irrigation methods such as flood or surface irrigation, include the reduction of water evaporation. One of the biggest challenges in dry regions is the evaporation of water from the soil surface. Since the water is transferred to the depth of the soil and is not exposed to air or direct sunlight, evaporation is significantly reduced. Efficient water use is another benefit of this method. Water is delivered directly to the plant roots, making water consumption more precise and optimized. This is particularly important in regions with limited water resources. The reduction in water wastage is significant in this method. In traditional methods like surface irrigation, a large amount of water is lost due to evaporation, insufficient infiltration into the soil, or lateral flows. However, in subsurface irrigation, these losses are minimized because the water directly reaches the depth of the soil and the roots [9, 10].

Another benefit of this method is increased crop productivity. By precisely delivering water to the plant roots, plants can grow better, and their water needs are accurately met. This leads to higher crop yield per unit area, especially in conditions where water is highly limited. The reduced need for frequent irrigation is also an advantage of this method. Since water is stored in the root zone and gradually absorbed by the plants, the need for frequent irrigation is reduced compared to surface irrigation. This not only prevents water wastage but also reduces the costs associated with irrigation. Improved soil structure is another positive effect of subsurface irrigation. The use of this method can help improve the soil structure. When water reaches the soil depth, it increases soil permeability and improves its aeration. This helps the roots receive oxygen easily and optimizes nutrient absorption processes [11].

Although subsurface irrigation has many advantages, there are challenges to its implementation in some areas. One of the challenges is the high initial installation costs of the system. Installing pipes or strips for irrigation underground requires a significant initial investment, which may not be affordable for many farmers. Additionally, the maintenance and repair of these systems may be more complicated than traditional methods. Another issue with this method is the need for precise and timely monitoring. If the system is not installed properly or malfunctions, diagnosing problems in the soil depth is more difficult than with surface irrigation methods. Moreover, clayey soils or very heavy soils can cause pipe blockages and reduce the system's performance [9, 12].

In Iran, considering the dry and semi-dry climatic conditions in many regions, the use of subsurface irrigation systems can be an effective solution for reducing water consumption and improving agricultural productivity. Especially in provinces like Yazd, Kerman, South Khorasan, and Sistan and Baluchestan, which face severe water shortages, this method can significantly help reduce water losses and increase agricultural efficiency. Since evaporation from the soil surface is very high in these regions, the use of subsurface irrigation can be a great help in addressing this problem.

4. SMART DRIP IRRIGATION

Smart drip irrigation is an advanced irrigation technology that uses sensors, data, and intelligent algorithms to precisely and optimally adjust the timing and amount of irrigation. This system is designed to automatically simulate soil conditions, water status, and the plant's actual needs, and then adjust the irrigation amount and timing accordingly. Unlike traditional irrigation systems, which are typically manually operated with fixed settings, smart drip irrigation dynamically monitors and responds to real-time changes [13].

One of the most important features of smart drip irrigation is the use of soil moisture sensors. These sensors can measure the moisture level of the soil in the root zone of plants and send the collected data to a central system. This data is then processed by the intelligent system to adjust the water consumption based on the plant's actual needs. In this system, irrigation only occurs when the soil needs moisture, rather than according to a fixed schedule. This feature helps prevent over-irrigation or under-irrigation, minimizing water consumption [14].

The advantages of this method, particularly in dry regions, are significant. First, reducing water wastage by using it precisely at the right time and place is especially crucial in arid climates where water scarcity is a major challenge. In this system, irrigation occurs only when the plant requires water, which leads to a reduction in water wastage and prevents excessive irrigation. This feature is particularly important in sustainable farming and in the face of climate change. Second, the improvement in irrigation efficiency in *this system is evident compared to traditional methods. In traditional irrigation, water is often spread on the surface, which can lead to high evaporation and insufficient infiltration into the soil. However, in smart drip irrigation, water is directed straight to the plant roots, which not only reduces evaporation but also makes nutrients more readily available to the roots, optimizing plant growth. Additionally, since irrigation only occurs when the plant needs water, this system ensures that the soil remains at optimal moisture levels for plant growth. The reduction in energy costs is another benefit of smart drip irrigation. Because irrigation is done precisely and in accordance with the plant's needs, the need for water pumps and water delivery systems is often reduced, which in turn reduces energy consumption and irrigation-related costs. Moreover, these systems can be connected to solar energy systems, which can play an important role in reducing costs and protecting the environment [15].*

Smart drip irrigation is also effective in reducing environmental damage. With this system, irrigation is directed only to the root zone, preventing water from being applied to unnecessary areas, such as the soil surface or non-agricultural land. This helps prevent the leaching of nutrients from the soil, pollution of water sources, and the growth of weeds. These systems can also use chemicals and fertilizers more precisely, ensuring that the correct amount of fertilizer reaches the plant roots and preventing contamination of groundwater [15, 16].

There are also challenges and limitations in implementing smart drip irrigation. One issue is the high initial installation costs. Installing smart systems requires specialized equipment and skilled labor, which can increase the initial investment. Moreover, the maintenance and repair of smart systems are more complex than traditional methods. If the sensors or control equipment fail or malfunction, the system may not function effectively and may require costly repairs [17].

However, in dry and semi-dry regions, such as Yazd, Kerman, and South Khorasan provinces, which face severe water shortages, this method can play a vital role in water resource management. Smart drip irrigation, by optimizing water use and reducing its wastage, can help farmers achieve high crop yields under water-scarce conditions. Additionally, this method can be effective in reducing costs and increasing production efficiency, as farmers can irrigate and provide nutrients to their crops in the most optimal way, based on the precise needs of the plants.

In summary, smart drip irrigation is an effective and sustainable solution for reducing water wastage, improving agricultural productivity, and lowering irrigation-related costs in dry regions. With technological advancements and the development of smart systems, this method can soon become a global irrigation standard, particularly in regions with limited water resources.

5. SOIL AND CLIMATE SENSORS

Soil and climate sensors are tools used to measure and record various environmental and physical data related to soil and climatic conditions. These sensors can assist farmers and researchers in accurately assessing the water and nutritional needs of plants, enabling them to make optimal decisions regarding water resource management. This technology is particularly valuable in arid and semi-arid regions where water scarcity and water management have become significant challenges [18].

Soil sensors typically include devices that measure soil moisture, temperature, pH, electrical conductivity, and other physical and chemical properties of the soil. These sensors can provide precise information about the soil moisture levels at different depths, root growth status, and the availability of nutrients for plants. One of the key advantages of using soil sensors is the ability to irrigate at the right time and with the correct amount of water. By measuring soil moisture, farmers can determine when plants need water and exactly how much should be added to the soil. This prevents water wastage and significantly improves agricultural productivity [19].

Climate sensors, which are typically installed in open fields, can measure climatic variables such as temperature, relative humidity, wind speed, solar radiation, and precipitation. These data enable farmers to monitor environmental conditions at the farm level and use the information to predict future conditions and make appropriate decisions. For example, using climate sensors, it is possible to predict when rain is likely, which can help farmers adjust irrigation systems intelligently [19, 20].

The benefits of using soil and climate sensors in irrigation management and agriculture, especially in dry and semi-arid regions, are striking. One of the most significant advantages is the conservation of water resources. With these sensors, farmers can determine the precise amount of water required by plants and avoid unnecessary irrigation. This is particularly crucial in regions with water scarcity. Additionally, these *sensors help farmers determine the exact amount of fertilizer and nutrients needed for plants, which in turn optimizes fertilizer use and reduces groundwater pollution [20].*

Greater accuracy in predicting plant needs is another advantage of these systems. Traditionally, farmers determine irrigation timing and amounts based on experience and surface observations. However, with the use of sensors, irrigation is done more precisely and according to the actual needs of the plant, improving plant growth conditions and ultimately increasing crop yield. Moreover, optimizing soil moisture and nutrient management leads to increased productivity and better-quality crops [21].

Soil and climate sensors also allow farmers to manage their irrigation systems intelligently and adjust them based on up-to-date and accurate data. This helps farmers make decisions based on scientific, precise information, reducing reliance on experiential forecasts [18].

However, there are challenges and limitations in using soil and climate sensors. One major issue is the high cost of purchasing and installing these systems. While these tools significantly enhance agricultural productivity, the initial costs of purchasing and installing sensors can be a challenge for small-scale farmers or low-income producers. Additionally, maintaining and repairing these systems, especially in harsh climates such as extreme heat or cold, can be problematic and requires continuous monitoring and care. Furthermore, these technologies rely on data accuracy and constant communication with central systems, which may be less effective in regions with limited access to the internet or communication networks. In such cases, data needs to be stored locally and transferred at appropriate times, presenting a significant challenge [22].

Nonetheless, the use of soil and climate sensors in the dry and semi-dry regions of Iran can have a profound impact on water resource management. In provinces like Yazd, Kerman, and South Khorasan, which face significant water shortages, these sensors can help farmers carry out precise and intelligent irrigation. This technology can also significantly reduce water consumption and improve agricultural performance, helping farmers achieve higher productivity in challenging climatic conditions.

In conclusion, soil and climate sensors, as advanced and innovative tools in agriculture, can greatly contribute to optimizing irrigation and reducing water consumption in dry and semi-dry regions. This technology, in addition to increasing agricultural productivity, allows farmers to make more precise, data-driven decisions, which ultimately improves the sustainability of agriculture in these regions.

6. *INTERNET OF THINGS (IoT)*

The Internet of Things (IoT) is an emerging technology that has the potential to revolutionize the management of water resources and irrigation in agriculture, especially in dry and semi-arid regions. In this technology, various devices and sensors are connected to a wireless communication network, transmitting real-time and accurate information related to environmental and irrigation conditions. This data may include soil moisture levels, temperature, wind speed, precipitation, solar radiation, and many other parameters. IoT systems collect and process this data, using it to enhance water resource management and optimize water usage in agriculture [23].

The use of IoT in agriculture, particularly in regions facing water scarcity, is of great significance. One of the key benefits of IoT in agriculture is the continuous and timely collection of data. These devices can consistently gather information from agricultural fields and send it to farmers or management systems. With this information, farmers can be informed about soil moisture levels, plant water needs, and environmental conditions in real-time, enabling them to make more accurate decisions regarding the timing and amount of irrigation. This is especially important in conditions where climate change leads to instability in water resources [24].

Another advantage of using IoT in agriculture is the high precision in irrigation management. IoT systems allow farmers to irrigate based on the actual water needs of plants. For example, in the past, farmers might have relied on personal experience or general predictions to decide when to irrigate, which could lead to water wastage or insufficient irrigation. With IoT, irrigation is done based on accurate and real-time data from the soil and plant conditions, resulting in water savings and increased agricultural productivity [23].

A distinctive feature of IoT in agriculture is its ability to predict conditions. By collecting and analyzing environmental data, IoT systems can make predictions about changes in soil moisture, the likelihood of rainfall, and temperature variations. These predictions help farmers adjust irrigation schedules more optimally. For instance, if the system predicts rain in the coming days, farmers can delay irrigation, *preventing water wastage. This capability is especially useful in dry and semi-arid regions with limited water resources [25].*

Cost reduction is also another benefit of using IoT in irrigation. Typically, irrigation in agriculture requires the use of energy sources such as water pumps. With IoT, farmers can irrigate at optimal times based on the precise needs of the plants, which reduces energy consumption and the costs associated with irrigation. Furthermore, IoT systems can lower maintenance costs and increase efficiency because they automatically monitor data, reducing the need for manual, time-consuming checks by farmers.

Integration with other technologies is another important feature of IoT. IoT systems can easily integrate with other agricultural systems such as drip irrigation, temperature and humidity control systems, and even weather forecasting systems. This integration makes overall agricultural management more efficient and coordinated. Ultimately, by consolidating all this data, farmers can make smarter decisions about water usage, optimal planting and harvesting times, and improving product quality [23].

IoT in agriculture also facilitates remote monitoring and management. Farmers can access system data from anywhere, even from a distance, and control irrigation and other environmental factors. This feature can be particularly useful for farmers operating in remote or expansive areas. Additionally, this technology helps farmers quickly identify and resolve issues as they can be immediately alerted to any unexpected changes in data [24].

However, there are challenges and limitations to using IoT in agriculture. One of the challenges is the high initial cost of installing IoT systems. These devices typically require significant upfront investment and specialized installation. Moreover, this technology relies on stable communication networks and access to the internet, which may pose challenges in some areas. For IoT systems to function properly, high-speed internet and reliable communication networks are needed, which may not always be available, particularly in rural or remote areas. Furthermore, maintaining and providing technical support for IoT systems can be challenging. These systems require complex technology that needs periodic repairs and updates, which may require farmers or operators to consult specialists for technical issues.

7. *USE OF SALINE OR RECYCLED WATER SOURCES*

The use of saline or recycled water sources is considered one of the modern strategies for managing water resources in arid and semi-arid regions. In these areas, which face a shortage of freshwater resources, the use of non-fresh or recycled water has emerged as a significant option to meet the agricultural water needs. These sources include saline water from seas, saline wells, and recycled water from urban or industrial wastewater, which were traditionally not used in agriculture due to their low quality. However, with advancements in science and technology, these sources are increasingly being utilized in agriculture [26].

Saline water refers to water with a high concentration of dissolved salts, making it unsuitable for conventional agriculture. However, in recent years, methods have been developed for treating and optimizing the use of saline water in agriculture. One such method is the use of salt-tolerant plants, which have the ability to grow and thrive in conditions where other plants cannot. These plants can typically utilize saline water for their growth with minimal harm to the soil and environment. For example, plants such as certain types of algae, desert plants, and specific fruit trees can grow well in saline environments, providing agricultural yields with lower costs and higher productivity [27].

Recycled water is also increasingly being considered as a water source for agriculture. Wastewater that has been treated and recycled to a suitable quality can be used for irrigation. This water is especially valuable in areas where freshwater resources are limited, and it serves as a supplementary source to meet the water needs of plants. Since recycled water typically contains additional nutrients such as nitrogen and phosphorus, it can act as a natural fertilizer, reducing the need for chemical fertilizers. In this way, in addition to providing the water needed by plants, these sources can indirectly help improve soil quality and increase its fertility [28]. The advantages of using saline and recycled water in agriculture, particularly in dry and semi-arid regions of Iran, are clearly evident. One of these advantages is the conservation of freshwater resources. Since freshwater resources are severely limited in many of these areas, the use of saline and recycled water can help reduce pressure on freshwater supplies, conserving it for other uses. Additionally, these sources enable farmers to increase their irrigation volumes without putting excessive strain on natural water resources [29].

Moreover, another advantage is the reduction of water wastage. Using recycled water, which is commonly found in wastewater, means reusing water that would otherwise be lost to nature. This not only helps conserve water resources but can also be significantly effective in meeting agricultural water needs in regions facing water shortages [30].

In this regard, increasing agricultural productivity is another benefit of this method. Recycled water usually contains additional nutrients that can be beneficial for plant growth. These nutrients act naturally as fertilizers, especially for plants growing in nutrient-poor soils, eliminating the need for expensive chemical fertilizers. Additionally, using saline water to irrigate salt-tolerant plants can increase the production of specific crops such as medicinal plants, certain fruit trees, and salt-tolerant vegetables [31].

In some projects, the use of saline or recycled water in agriculture has also led to reduced production costs, as farmers can utilize cheaper and more accessible water sources instead of expensive freshwater. Moreover, recycled water, due to its additional nutrients, reduces the costs associated with purchasing and using chemical fertilizers [28].

However, the challenges and limitations of using saline or recycled water must also be considered. One of the major issues is the negative effect of saline water on soil. Long-term irrigation with saline water can lead to an increase in soil salinity, which in turn can reduce soil fertility and agricultural productivity. To address this problem, the use of advanced treatment technologies and proper management of saline water is essential to minimize its negative impacts on the soil [30].

Maintenance and treatment of recycled water can also present another challenge. The wastewater treatment process can be costly and require specific equipment and technical expertise. Therefore, to use this water in agriculture, efficient treatment and maintenance systems must be designed to ensure the water quality is preserved and no contamination or harmful substances are introduced to the soil and agricultural products [32].

8. *RESULTS AND DISCUSSION*

The use of modern irrigation technologies, such as subsurface irrigation, smart drip irrigation, soil and climate sensors, and the Internet of Things (IoT), can have positive impacts on water resource management and agricultural productivity in arid and semi-arid regions. These methods, particularly in areas like Iran, which face water scarcity, have the potential to create significant changes by reducing water wastage and increasing crop yields. Subsurface irrigation, by reducing evaporation and optimizing water use, enables farmers to achieve better performance with minimal water consumption under water-scarce conditions. On the other hand, smart drip irrigation, through the use of moisture sensors and intelligent data, automatically adjusts the timing and amount of irrigation, helping to prevent water wastage. Additionally, the use of soil and climate sensors, along with the IoT in agricultural management, enhances decision-making and enables optimized irrigation and environmental condition prediction through the collection and processing of data.

9. *CONCLUSION*

In general, all of these technologies can be considered effective and efficient solutions to address the challenges of water scarcity in agriculture, particularly in arid and semi-arid regions. These technologies optimize the use of water resources, significantly reducing water consumption, and thus help manage limited water resources more effectively and sustainably. Along with reducing water consumption, these technologies can enhance agricultural productivity, as smart and precise irrigation adjusts the plant's water needs based on environmental conditions and soil status, preventing resource wastage. Additionally, these systems can contribute to reducing irrigation and energy-related costs, especially in areas facing severe water and energy limitations. In Iran, where many provinces struggle with water scarcity crises, implementing these technologies can serve as a long-term and sustainable solution for optimal water resource management. This approach not only holds importance for preserving natural resources but can also strengthen food security and enhance agricultural production, especially in the face of climate change and water shortages, which pose serious threats.

10. *SUGGESTIONS*

To achieve more sustainable and efficient agriculture in the arid and semi-arid regions of Iran, several recommendations can be considered. The first step is to encourage investment in modern infrastructure. Installing underground and smart irrigation systems requires initial investment, and the government and relevant institutions should encourage farmers to adopt these technologies by offering financial incentives and technical support. In this regard, training and empowering farmers to effectively use these technologies is crucial. This training should particularly focus on the installation and maintenance of smart systems, and can be carried out through collaboration with universities and research centers. Expanding internet networks and communication infrastructure also plays a key role in the success of these projects. To effectively use IoT systems and smart sensors, the development of internet and communication networks in rural and remote areas is necessary.

This can improve access to information and help manage water resources more precisely. Additionally, further research and development in the field of irrigation technologies and their improvement, especially under Iran's specific climatic conditions, can enhance the efficiency of these systems. Research in this area should specifically focus on optimizing water consumption and adapting to environmental conditions. Finally, supporting farmers in using renewable energy sources such as solar energy can help reduce energy costs while also minimizing environmental impacts. In particular, the use of solar panels in smart irrigation systems not only reduces costs but also moves toward greener and more sustainable agriculture. Implementing these suggestions can lead to more sustainable and efficient agriculture in Iran's dry and semi-dry regions, positively impacting water resource management and increasing agricultural production.

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