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Review

Agricultural and Technology-Based Strategies to Improve Water-Use Efficiency in Arid and Semiarid Areas

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Abstract: Justification: Water-use efficiency (WUE) is the amount of carbon assimilated as biomass or grain produced per unit of water the crop uses, and it is considered a critical factor in maintaining the balance between carbon gain and water loss during photosynthesis, particularly in the face of global warming and drought challenges. Improving agricultural WUE is essential for sustainable crop production in water-scarce regions. Objective: This article explores the significance of WUE enhancement in agriculture, especially under drought conditions, and discusses various strategies to optimize WUE for improved crop productivity. Methods: We searched the scientific literature for articles on water-use efficiency published between 2010 and 2023 and selected the 42 most relevant studies for a comprehensive overview of strategies, technologies, and approaches to investigate sustainable agricultural practices to improve water-use efficiency in agriculture, particularly focusing on agronomic methods such as mulching, cover crops, canopy management, deficit irrigation, and irrigation modernization. Results: This review highlights several practical techniques for enhancing WUE, including sustainable irrigation practices, crop-specific agronomic strategies, and innovative technological solutions. By adopting these approaches, farmers can improve water management efficiency, reduce crop vulnerability to water stress, and ultimately enhance agricultural sustainability. In conclusion, improving water-use efficiency is an essential factor for ensuring food security in the face of climate change and water scarcity. By implementing innovative strategies and exploiting the power of technology, we can enhance WUE in agriculture, optimize crop production, conserve natural resources, and contribute to a more sustainable future.

Keywords: water-use efficiency; agricultural water use; crop production; agronomic practices

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1. Introduction

Water scarcity, or drought, is a crucial constraint on crop production in arid and semi-arid regions worldwide. Crop production is dependent on water availability, and disturbances in water supply may directly impact 40% of the crops grown in irrigated regions. [1]. It is projected that water consumption will increase by 50% by 2050, while half of the global population may experience severe water scarcity by 2030 [2,3]. Renewable freshwater resources are limited, and their geographical distribution is not fair enough. Conversely, the global population is increasing by approximately 73 million people annually [4], while the extraction of freshwater (which has already tripled since 1965) is growing at a rate of 64 km^3 per year [5]. In addition, aridity is a significant concern for the global community in terms of its economic, social, and environmental impacts, and ultimately, this issue impacts global food security, socioeconomic stability, and sustainable development [6]. This issue is most prevalent in Africa, the Middle East, and South Asia [7]. The enhancement of agricultural production and WUE in arid and semi-arid regions poses a significant challenge.

Water applications below the requirements of the evapotranspiration level are recognized as deficit irrigation [8]. Several agricultural practices (minimum tillage, crop residue

incorporation, mulching, and the implications of advanced irrigation methods) are being considered to improve WUE [9–12]. However, the potential and application of each technique are based on the soil type and environmental conditions. The production of more food with less water can only be accomplished with better agricultural and agronomic management strategies [13]. Climate change severely affects water resources in several parts of the world, including the Mediterranean, Europe, Central and Southern America, and Southern Africa [14]. Climate change leads to increased runoff in water-stressed regions, such as southern and eastern Asia [15]. Therefore, under such circumstances, it is imperative to implement more effective water management techniques. Insufficient water and limited nutrient availability can often hinder the growth and productivity of crops in agro-ecosystems [16–18]. This is because many cereals and fodder crops are highly susceptible to water and nutrient deficiencies during their vegetative and reproductive stages [19,20]. However, an overabundance of water can lead to higher production costs and environmental pollution, as it can cause fertilizers to leach into the environment [21,22].

WUE is commonly regarded as a crucial factor affecting crop yield under stress and as a component of crop drought resistance [23]. The term "more crop per drop" has been used to suggest that rainfed plant production can be enhanced by maximizing the utilization of each unit of water [24,25]. Crop residue incorporation, mulching, and the application of drought-tolerant rhizobacteria alongside the co-application of biochar and compost can play an integral role in increasing soil water holding capacity, soil water retention porosity, and nutrient content [26–28]. Meanwhile, deficit irrigation, irrigation scheduling, and remote sensing provide site-specific water requirements, and according to each stress level, water applications can be applied [29,30]. Moreover, automated irrigation systems adjust the timing of irrigation applications in real time, taking into account the availability of soil water in the root crop zone [29]. This approach significantly enhances WUE by conserving a significant amount of water. Meanwhile, deficit irrigation is a simple method to enhance economic productivity when the water supply is limited, although it necessitates several modifications in the agricultural system due to the lower water availability [31].

Therefore, the main objective of this study was to summarize the potential impact of each sustainable approach, including agronomic, irrigation management, and advanced technical measures, on soil WUE under both arid and semi-arid conditions. For this study, we searched the literature by encompassing the period from 2010 to 2023 by using search engines such as Web of Science, ScienceDirect, and Google Scholar. The following keywords were used for the literature search: "water use efficiency", "water retention", "plant available water", "arid", "semi-arid", "soil hydraulic properties", "soil fertility", and "crop growth". Moreover, we also went through the citations and the reference list of the selected papers to ensure the availability of all related studies. After screening the downloaded manuscripts, we finalized the 42 most relevant studies and analyzed their results with respect to each followed technique.

2. Strategies to Improve WUE

2.1. By Agronomic Methods

The depletion of irrigation resources heightens the need to increase WUE. Hybrid cultivars with improved WUE should be chosen in water-limited areas to increase water production per unit area. Through resource allocation optimization, agricultural practices, particularly timely sowing and suitable crop cultivar selection, improve WUE. Timely sowing of wheat maximizes yield unit experimentation, but late sowing lowers both WUE and grain production [32,33]. Planting/transplanting at different times during high and low evaporative demand periods can further improve WUE by reducing groundwater usage. This emphasizes the significance of cultivar selection and strategic timing in agricultural practices, as noted by numerous studies [34–38].

Techniques for conserving moisture are frequently used to increase yields in situations where water is scarce. Using compartmental bunds, ridges, and furrows instead of flatbeds significantly improved the sorghum yield components in Bijapur vertisols [39].

This was explained by the fact that these techniques made more moisture and nutrients available. Because the zero-tillage technique improves soil structure, increases organic matter content, fosters soil health, lowers erosion, and conserves moisture, it also enhances WUE [40]. Especially in rainfed areas, intercropping protects against crop failure while also diversifying cropping systems and optimizing water and resource utilization. The increased WUE is a result of higher yields in intercropping systems, such as maize (*Zea mays*), soybean (*Glycine max*), maize–mungbean (*Vigna radiate*), and maize–potato (*Solanum tuberosum*), as opposed to mono-crops [41,42]. Because of their higher grain yields in comparison to water consumption for biomass, intercropping configurations such as moth bean between paired rows of pearl millet (*Pennisetum glaucum*) and green gram between paired rows of pigeon pea display better WUEs [43,44]. Furthermore, under various water conditions, particular intercropping combinations like rice (*Oryza sativa*), lentil (*Lens culinaris*), maize+cowpea (*Vigna unguiculata*), rice–coriander (*Coriandrum sativum*), and maize+cowpea show greater water-use efficiencies [45,46]. Crop geometry and row spacing optimization can improve yields and water-use efficiency. Research by Karrou (1998) and Jones (2010) showed that reduced evaporation losses and faster canopy growth can result in increased yields and better water-use efficiency when planted with narrower row spacings and other alternative planting techniques, such as twin-row spacing [47,48]. In addition, studies conducted by Patil and Sheelavantar (2000) and Rathore et al. (2008) showed that crop geometries also play a key role in WUE for instance they concluded that inter-cropping of sorghum (plant to plant distance 45cm) and bajra (plant to plant distance (12 cm) significantly enhanced crop canopy cover and nutrient utilization which ultimately boosted crop WUE [39,49]. Chickpeas (*Cicer arietinum*) grown with a wider row spacing of 45 cm had higher total moisture and moisture use efficiency than those grown with a narrower spacing of 30 cm [50]. These results highlight the significance of crop geometry and row spacing in maximizing WUE in agriculture.

Phosphate-solubilizing bacteria (PSB) and rhizobium inoculation greatly increase legume crops' consumptive consumption and WUE. In comparison to a single inoculation or no inoculation, combining rhizobium and PSB inoculations in chickpea significantly boosts both variables [50]. Singh et al. (2004) highlighted the importance of efficient weed control in raising WUE by showing that weed-free treatments in chickpea production exhibit higher moisture use efficiency [51]. Similar to this, Nadeem et al. (2007) found that manual weed treatment in wheat resulted in maximum WUE, which was linked to decreased weed density and higher grain production [52]. Furthermore, Reddy et al. (2008) discovered that pigeon peas grown under particular intercoalition techniques and herbicide treatments had higher WUEs, which could have been a result of decreased weed density and increased seed output [53]. Together, these findings highlight how crucial it is to optimize WUE in agricultural practices by employing both effective weed management and inoculation strategies. The efficiency of water consumption and crop yield are strongly impacted by fertilizer application. Research conducted by Kumar et al. (2000) and Rathore et al. (2008) indicates that growth and development are boosted, especially in irrigated and arid regions, by nitrogen, phosphorus, and mixtures of chemical and organic fertilizers or biofertilizers [49,54]. Raising nitrogen levels is associated with a significant improvement in WUE in crops such as pearl millet [43,55]. This improvement is ascribed to increased root system activity and nutrient translocation. Studies have also shown that fertilization strategies containing organic, phosphorous, and nitrogen additions improve the efficiency of water consumption in crops such as sorghum, wheat, amaranth, rice, and cotton [36,56–58]. Although lower nitrogen dosages may compromise efficiency due to decreased transpiration and soil moisture extraction, higher yields obtained with correct fertilization contribute to enhanced water-use efficiency [59].

In conclusion, effective agricultural techniques are essential for optimizing water-use efficiency and producing profitable harvests. These techniques range from selecting high WUE types and ideal sowing times to crop establishment strategies. Enhancing water-use efficiency and production requires several strategies, including close row spac-

ings, zero tillage techniques, compartmental bunds, ridges, furrows, and appropriate irrigation management. By preserving water and enhancing soil health, using fertilizers, intercropping schemes, and bed planting methods contribute to sustainable agricultural production.

2.1.1. Maximizing the Utilization of Green Water

Green water is defined as the amount of rainwater that infiltrates into the plant roots zone, which is used for plant transpiration, growth, and biomass production. Overall, the goal of green WUE is to maximize the water availability for plant transpiration demands and minimize excessive water flows into the soil surface, including evaporation, runoff, and percolation beyond the root zone. Moreover, higher green WUE can easily provide more available water for agricultural food crops and forest trees. Reducing the amount of water that precipitation deposits into the soil is crucial for reducing the demand for plant irrigation. Techniques for raising the total amount of water available to plants can be connected to the enhanced capacity of soils to retain water. The physical and chemical structures of the soil can be enhanced by adding organic matter and avoiding needless soil water loss. Additionally, mulching can improve the quantity of water accessible to plants with more extensive and deeper root systems that have more drought-adapted rootstocks, as well as decrease direct soil water evaporation. A popular sustainable agronomic technique for enhancing the general qualities of soil and reducing soil erosion is organic mulching. In addition to straw mulch, which is reasonably priced and readily available, other excellent options for mulching include compost made from waste materials and agricultural waste [60]. Mulching has been shown to have a number of benefits, including (i) improved plant nutrient status and nutrient release efficiency, which allows for a reduction in the amount of fertilizer applied [60–63]; (ii) weed control, which allows for a reduction in the amount of herbicide applied [64,65]; (iii) the prevention of soil erosion by improving soil structure and decreasing soil compaction [62,66,67]; and (iv) increasing biodiversity, which can encourage beneficial insects to prevent pests [68,69]. According to one study, using organic mulches improved yields while also lessening the impact of disease and insects [70]. Research on the effects of mulching on agricultural water uptake and retention and, consequently, crop WUE has been few thus far. WUE is the ratio of total water used to agricultural productivity. Conversely, the total amount of crop water used includes the amount of water that is lost straight from the soil without being used by the plant. Gregory (2004) pointed out that agronomic practices like mulching can avoid or reduce the overall quantity of crop water used, which is produced by soil evaporation, runoff, and leaching. Similarly, mulches can change soil reserves, lower soil evaporative losses, and improve water infiltration into the soil [71]. These results align with certain reviews [72,73] that showed how mulching or surface residue management might raise WUE by reducing runoff and soil evaporation in other crops.

Compost-mulched soils showed reduced evaporation rates, increased water permeability, and increased water storage capacity compared to bare soil. According to Agnew et al. (2002), mulches that have moisture levels that are roughly 5% higher in the upper half of the soil profile (0–30 cm) help retain soil moisture early in the growing season. Rather than using cover crops or mechanical tillage, the highest soil moisture was found under straw mulch on sandy soils [62]. On an annual average, the covered soil had a 3.4% higher soil moisture content in the 0–60 cm range than the tilled soil. In addition, a 50% drop in soil penetration resistance was observed, which was related to soil compaction [67]. Direct soil evaporation can account for up to 20% of water use, indicating that covered soil may improve plant water availability [74].

In summary, mulching is a useful soil management technique that lowers soil water loss and increases WUE. However, there is currently no way to measure how mulching helps grapevines conserve water and increase WUE. It is challenging to make generalizations regarding the quantity of water saved or the decreases in irrigation water requirements because of the wide variations in the impacts of mulching based on soil types, rainfall

patterns, and evaporative demands [75]. That being said, different kinds of mulch may differ in their ability to retain water as well as in evaporative loss [76].

2.1.2. Cover Crops

Often grown for their positive impacts on the soil rather than for harvesting, cover crops are sometimes known as catch crops or green manure. These are non-commercial plants and grown for a variety of agronomic and ecological benefits in between cash crop seasons. Cover crops improve soil health, promote biodiversity, inhibit weed growth, reduce erosion, and improve nutrient cycling in agricultural settings [77]. Terrestrial ecosystems typically maintain a layer of plant residue on the soil's surface throughout the year, which affects seedling emergence and vegetation succession [78]. Using cover crops is a popular recommendation for eliminating surplus water and nutrients from the effective root zone. Additionally, especially during the months when cash crops are dormant, they decrease soil erosion and water flow, improve soil fertility and structure, and strengthen soil structure [79]. However, implementation of these systems is limited in semi-arid regions, particularly in those with yearly rainfall of less than 1000 mm, as the purported disadvantages are believed to outweigh the benefits [80]. Therefore, a complete understanding of crop rooting depths and soil water-holding capacity is necessary in order to advise on their utilization effectively. In order to maximize benefits and minimize drawbacks, species and variety selection is also crucial [81].

Numerous researchers have assessed the effects of Mediterranean legume-grass mixes as interrow cover crops on soil stability and crop performance [82–85]. In water-limited settings, ground coverings can be managed during the early stages of vegetative growth. This improves the quality of the plants and must by lowering the quantity of canopy leaf area and subsequent transpiration losses [86,87]. These approaches need to be put into practice right now to prevent severe water stress, which could negatively impact fruit set or cause premature defoliation [83]. Cover crops, however, clearly improve soil properties and alter the water dynamics in the soil profile [88]. Pou et al. (2011) investigated the effects of several cover crops on plant development, production, quality, and WUE. Despite the fact that cover cropped plants initially had leaf gas exchange rates that were either greater or similar to those of regular tillage, WUE did not significantly differ among treatments. However, because they were consuming less water due to having smaller leaf areas, plants with cover crops later in the growing season showed more constant values of WUE and leaf gas exchange [81].

In summary, cover crops increase soil health, reduce erosion, and promote sustainable practices-all of which help to raise agricultural WUE. They strengthen the soil's structure, decrease compaction, and increase water retention, which lowers evaporation. Moreover, cover crops reduce soil erosion, surface runoff, and atmospheric nitrogen fixation-all of which reduce the need for chemical fertilizers. Notwithstanding these advantages, there are nonetheless disadvantages, like the requirement for water, rivalry with revenue crops, upfront costs, and management issues. Cover ls have the potential to significantly increase WUE in agriculture, but addressing these challenges will need mindful planning and effective management strategies.

2.1.3. Canopy Management

Enhancing WUE via canopy management is essential for sustainable agriculture in order to control the microclimate surrounding the clusters and, consequently, the yield, quality, and hygienic conditions of the fruit. Many studies have examined how plant architecture affects canopy radiation distribution and plant productivity [89–93]. Adjusting row spacing, selective pruning, and optimizing leaf orientation are some of the techniques that increase WUE by maximizing transpiration and reducing soil water evaporation [72]. Different plant species have different leaf arrangements, and transpiration rates are influenced by the canopy's structure, which influences solar radiation exposure [94]. Transpiration affects water consumption and is controlled by physiological and anatomical characteristics.

Transpiration grows linearly with the canopy leaf area, impacting dry matter production and photosynthesis [95]. Photosynthesis and transpiration rates are influenced by mutual shadowing among leaves, especially in crops where the leaf area index (LAI) is higher than four [72]. Since the canopy completely blocks out light, evaporation from the soil surface (E) grows more slowly as the leaf area index (LAI) gets closer to four [96–98].

WUE substantially and positively depends on incoming light interception [92]. However, only a small number of studies have concentrated on the impacts of the canopy on leaf gas exchange [91,93,99] and WUE. Additionally, this study demonstrated that the WUE was lowest on shaded leaves inside the canopy. The optimization theory for leaf gas exchange was called into question by a closer examination of the relationship between leaf gas exchange parameters and microclimatic conditions for various canopy positions [100]. These findings not only highlighted the challenges in estimating the WUE of the entire plant using WUE parameters at the leaf level, but they also offered hope for enhancing the WUE of the entire plant through canopy management techniques like selective pruning. The adoption of micro-irrigation decreases soil water evaporation and improves WUE while using less water. While micro-irrigation reduced water usage by 37% and lowered the yield by 21% in cotton, it was able to reduce water use by 23% and improve output by 37% in wheat [101]. Using a micro-irrigation system restricts practically all of the evaporation components from the canopy and lowers the level of soil water evaporation from between plant rows early in the growing season [72,101]. This shows that the WUE can be altered by systemic water management and have a favorable impact on the WUE in areas with irrigated crops. Research by Hatfield and Dold (2009) explored the proper mechanism of canopy-level techniques to raise the WUE in agricultural systems [72]. Furthermore, Michelon et al. (2020) discussed sustainable water management strategies for raising the WUE in agricultural crop production [94]. By concentrating on factors like leaf net photosynthesis and stomatal conductance, canopy management techniques, which include controlling crop water consumption and root system management, maximize water usage [72]. Customized field management strategies improve agricultural WUE even more and ensure productive and sustainable agricultural systems [94].

3. Irrigation Strategies and WUE

3.1. Deficit Irrigation (DI)

This irrigation strategy was developed with the intention of using less water, which generally correlates with the classical irrigation strategy that aims to maintain a certain degree of water deficit. This strategy typically results in crop quality being maintained or improved at the expense of a small decrease in potential yield but with a significant reduction in the amount of water applied. Deficit irrigation specifically refers to applying water in smaller amounts than what the plants or crop evapotranspiration (Etc) [102].

This strategy has two variations:

I. Regulated deficit irrigation.
II. Partial root zone drying.

3.1.1. Regulated Deficit Irrigation

This is based on the idea that a plant's susceptibility to water stress (quality or yield) varies during its phenological life. Thus, irrigation at a lower amount than ETc. levels during particular times can significantly reduce vigor and enhance harvest quality while also using less water [103,104]. This deficit irrigation method can be used to achieve various goals at various phenological stages, such as causing anthocyanin accumulation [105] or lessening the vigor of fruit cell division so its size [104]. With this irrigation approach, irrigation must be controlled based on environmental data in order to maintain the soil and plant water status within a specific range [102]. Excessive water reduction in this strategy can cause severe yield losses and poor quality. On the other hand, excessive water can increase the vigor and so suppress the advantages of this strategy [102,106].

3.1.2. Partial Root Zone Drying

Conversely, partial root zone drying involves wetting and drying approximately half of the plant's root system in cycles of 8–14 days, depending on the soil type. In order to irrigate one half of the root system while leaving the other half to dry in a single cycle and switch sides for wetting and drying in the subsequent cycle, this system needs two irrigation lines, each controlled by a separate valve. While the drying half is associated with a decrease in stomatal conductance, the wet side gives the plant enough water to prevent water stress [107]. This tactic is predicated on the understanding that roots exposed to water stress generate hormone signals, principally abscisic acid, which is a hormone that causes stomatal closure and growth inhibition [107,108].

4. Irrigation Modernization

Irrigation modernization implies the replacement of outdated irrigation infrastructure and procedures with current equipment and technology. Enhancing water conservation, streamlining water distribution systems, and reducing labor and operating costs are the main goals of modernization, which will support sustainable farming practices and farmers' livelihoods [6]. On the other hand, irrigation system automation entails the use of equipment and machinery to support irrigation procedures with the least amount of human involvement possible, except for routine maintenance and monitoring duties.

4.1. Water Distribution System

In the Middle East, irrigation has been a common longstanding practice as here irrigation water distribution system, depends on a vast network of canals, dams, and reservoirs fed by the Indus River and its tributaries, is essential to the country's agricultural sector. Pakistan's irrigation water distribution system is the largest in the whole world consisting of 16 million hectare area. Its largest component, the Indus Basin Irrigation System (IBIS), has three main canals, i.e., the Right Bank Outfall Drain (RBOD), the Left Bank Outfall Drain (LBOD), and the Indus River itself. Only the IBIS provides water to 8 million hectare land [109]. Despite obstacles including unequal distribution and ineffective operations, this system guarantees water delivery to agricultural areas across the country [110]. Ongoing efforts aimed to increase its efficacy upon equitable water distribution and better management practices [111]. Additionally, studies have highlighted how farmers compete with one another for water resources and how this affects agricultural productivity [112]. In Pakistan, irrigation systems are essential to maintaining agricultural livelihoods and guaranteeing food security, so research has examined the efficacy of drip irrigation systems in district Rawalpindi, Punjab, Pakistan, in terms of operational efficiency and capacity building for farmers; the significance of technical proficiency and sustainable practices in terms of optimizing water utilization [113]. Precise flow monitoring is essential for improving WUE because accurate water measurements are essential. By using technologies like automatic regulators and telemetry systems, these projects highlight the potential for WUE improvement and savings and highlight the necessity of ongoing modernization in both large-scale irrigation systems and on-farm operations. Seepage losses, especially in open-air clay channels, may contribute up to 14% of the total water used for irrigation projects. Furthermore, evaporation losses might present serious difficulties, especially in dry areas and large, open channels [114]. Therefore, one of the main goals of the modernization plan is to use different methods to mitigate these losses. These include the use of clay or rubber for canal linings, the restoration of concrete and earthen channels, the installation of gravity pipes to replace open channels, and improvements to the irrigation infrastructure on farms [111]. According to the proverb "You cannot manage what you cannot measure," precisely measuring the water delivered to farmers is a crucial part of improving WUE.

4.2. Irrigation Scheduling

Irrigation scheduling—the process of determining when and how much water to apply—has a direct impact on WUE. Irrigation WUE is decreased by applying more water than is necessary for plants to consume it at their best. Planning irrigations requires an understanding of plant water needs, which are dependent on a variety of factors like growth stage, weather, and canopy moisture. The meteorological element is illogical, seasonal, and occurs every day.

Utilizing a pressure bomb, one can ascertain the plant's water condition directly; alternatively, one can observe the stem sap flow and utilize that information to determine when to water the plant. Other indirect methods include using probes to measure the moisture content of the soil and estimating crop evapotranspiration (ET). Jones described the main techniques for scheduling irrigation [106]. In Australia, tensiometers and soil probes are the irrigation scheduling tools that are most frequently used [115]. Farmers that do not use scheduling software usually schedule irrigations based on past irrigation experiences. However, a prior study suggested that these farmers, who rely on the "rule-of-thumb", might be losing water [116]. One significant drawback of these soil moisture-based scheduling methods is that, although soil characteristics are known to vary across time and space, they only offer point-based measurements [117]. Due to technological breakthroughs like the internet, a range of computer-based irrigation scheduling tools have been developed to help farmers make decisions. These tools, such as WaterSense, WaterTrack Rapid, and IrriSatSMS, are widely used in developed countries [118]. Even though there are proven benefits to using these technologies to improve WUE, there are still barriers to their application, including their cost and complexity [115]. In recent years, more reasonably priced and versatile sensors have become available. So, scheduling irrigation is made easier with an automated irrigation system that has sensors and accurate metering.

4.3. Real-Time Control

Variations in the weather and soil composition can cause temporal and geographical variations in the infiltration features at the field scale. Most conventional irrigation methods aim to disperse water uniformly, which will produce a field-wide on-farm WUE that is similarly variable [119]. Because irrigation water is delivered uniformly throughout the soil surface in surface irrigation systems (furrow irrigation, for example), the diversity in WUE is more noticeable. Thus, real-time control and optimization—a notion that has long been used in other technical fields—has gained favor in the field of irrigation water management in recent years.

The process of evaluating measurements made during an irrigation event (such as the water movement in a furrow system) and making changes to that irrigation event in real time is known as real-time control in irrigation. This contrasts with traditional management approaches, which usually rely on past or historical measurements that are influenced by the infiltration characteristics that change over time. Real-time control is possible when the control procedure is automated to enable quick implementation of the feedback. However, optimization refers to the act of changing different irrigation system parameters in order to obtain the optimal result. This was previously accomplished by irrigator knowledge and experience, but due to recent advancements in computer capabilities, the usage of simulation models has increased [120]. Smart irrigation systems are surface watering systems that may be adjusted and improved in real time. They are seen to be superior to fully automated systems, which are primarily made to automate some functions in an effort to reduce the labor-intensiveness of irrigation. Irrigation systems that are traditional or conventional are linked to low WUE and a high manpower need. For example, adaptive real-time management has been proposed as a means of controlling temporal infiltration variability in surface irrigation systems [121–123]. In a commercial cotton field in Queensland, Australia, a real-time optimization system for furrow irrigation was tested, and it showed lower labor costs and increased WUE [124]. This system included

sensors to detect water movement along the furrow, an inflow rate monitor, telemetry to enable communication between various components, and a computing system with a simulation model. The commercial prototype of this system was tested in a field with commercial irrigation, and the results indicated that it can optimize application efficiency by controlling irrigation events by cut-off time [125].

Thus, it is evident that real-time control and optimization, especially for surface irrigation, are still at their infancy even in the irrigation sector of developed countries. However, considering the quantity of studies and the advancements made thus far, it is likely that it will become more significant in the future for the management of irrigation water and the enhancement of WUE.

5. Recent Potential Opportunities for WUE

Recent investments in research and development programs and general technological advancements have created new or developing potential for higher WUE in irrigated agriculture. This has taken the shape of both more affordable and somewhat accurate substitutes as well as innovative tools and methods.

5.1. Remote Sensing

Improving WUE in irrigated agriculture depends on the amount and time of irrigation optimization. Whether they are based on plants, soil, or meteorology, current scheduling techniques are usually expensive, labor-intensive, and difficult to automate [106]. Furthermore, they are frequently site-specific, which restricts their use to wide areas. However, because of its ability to integrate with Geographic Information Systems (GISs) and provide systematic data in both space and time, remote sensing has become more popular in studies on irrigation water management. New methods evaluate crop water status for irrigation scheduling using remotely sensed data. Evapotranspiration (ET) may be estimated over large areas more easily when satellite images and ground-based observations are used [119,126]. WUE augmentation is aided by Landsat thermal infrared (TIR) images, which offers insights into ET regional variability [127,128]. Although remote sensing is underutilized, it has the potential to evaluate actual crop ET at different scales, especially with the current Landsat-8 series and commercial satellites like Sentinel-2 and Planet [31]. Unmanned aerial vehicles (UAVs) or drones may also gather thermal and multispectral imagery, which offers a potential way to monitor agricultural water status [129]. When evaluating agricultural water status at different spatial scales, remote sensing outperforms conventional techniques. Drone technology is expected to become widely used as it is becoming cheaper, which will make it necessary to connect irrigators to remote sensors in order to take advantage of economies of scale. Hyperspectral sensors hold promise for ultra-high-resolution data collecting and streaming technology-enabled data synthesis in the future [130].

5.2. Communication Networking

Sensors are essential for collecting information about soil moisture and the weather, which helps improve agricultural practices, particularly irrigation management. In the past, manual techniques involving cables were expensive and time-consuming, which resulted in subsequent errors in water management. However, due to developments in technology and the availability of reasonably priced sensors, the use of wireless sensor technologies is expanding [130]. A variety of field characteristics, including soil moisture and the weather, can be monitored in real-time via wireless sensor networks, which are made up of sensor nodes and communication technologies [129,130]. Range and energy efficiency are two benefits of common agricultural communication technologies like ZigBee, Bluetooth, and WiFi. Because of its reliability, ZigBee is chosen for irrigation [131,132]. By monitoring soil conditions and transmitting information via 3G networks, these sensors improve WUE by enabling real-time irrigation system control [35]. Furthermore, pressure sensors in

wireless networks can be utilized to modify methods for detecting leaks in urban water systems for irrigation purposes [133].

Research is still being conducted to advance communication networks and sensor technology, which could lead to better agricultural services. Future communication network integration might make multipurpose uses possible, such as smart water meters for urban water delivery and irrigation [134].

5.3. Irrigation Water Productivity

Scientists have successfully developed high yield crop varieties through advances in plant breeding, which, when all other parameters stay the same, increases irrigation water productivity. In their investigation into the molecular genetics of improving plant WUE, ref. [135] concentrated on gene manipulation that influences stomatal development and root characteristics. Higher yields are also a result of genetically engineered types that are resistant to diseases and pests. Due to improved crop and water management, genetically modified cultivars, and plant breeding yield advances, the Australian cotton sector saw a 40% increase in water use productivity in just ten years [136]. When there is a water shortage, one tactic used is deficit irrigation, which involves using less water than necessary. According to a dairy region trial conducted in Victoria, Australia, lucerne under deficit irrigation fully recovers when full irrigation is restored, providing the best conditions for fodder development [137]. Ref. [138] discovered deficit irrigation techniques to improve WUE in a citrus crop experiment conducted in Spain. Similarly, ref. [31] promoted the use of deficit irrigation in China's water-scarce areas.

6. Water Consumption at the Basin Scale

6.1. WUE and Water Consumption at the Basin Scale

WUE is frequently regarded as essential for water conservation that benefits consumers and the environment. Higher WUE does not always result in net water savings, particularly when looking at basin-scale data [139,140]. What appears to be a loss in a basin context, such as deep drainage, might actually help groundwater recharge [119]. Contrary to expectations, increased on-farm WUE can decrease downstream water availability or deplete groundwater [139]. Expanded irrigated areas due to water-saving methods may result in higher water consumption at the basin scale [141,142]. In Morocco, for instance, crop rotations and increased acreage caused by subsidized drip irrigation resulted in increased water use [142]. Similarly, in India, the implementation of water-efficient techniques not only improved crop WUE in recent years but also reduced the overextraction of groundwater [140]. Initiatives for groundwater recharge are one way to achieve a balance between efficiency and conservation [143]. But encouraging water-efficient technology on its own might not be enough to cut down on the consumption of water overall [144,145]. Integrating incentives, rules, and conservation initiatives is necessary for effective measures [140,144]. Furthermore, although pressurized irrigation systems improve productivity, they also use more energy and produce more greenhouse gas emissions [146]. The adoption of these techniques may be impacted by rising energy costs, highlighting the necessity of comprehensive strategies for sustainable water management.

6.2. Factors Affecting Trends in WUE

Engineering and technological aspects encompass upgrading water distribution networks, on-farm irrigation development, scheduling, real-time control, optimization, and employing remote sensing and sensor communication networks. These actions primarily improve irrigation WUE by reducing water loss [147]. More recently, irrigation WUE has been enhanced by a multitude of commercially accessible hardware and software devices. Additionally, advancements in plant genetics have produced disease-resistant, high-yielding cultivars that promote higher WUEs [139,148]. Growing environmental awareness leads international governments to provide funding for water-saving initiatives, releasing the water that has been saved as natural flows. The dynamics of WUE are also

greatly influenced by socioeconomic factors, which highlight the adoption of new technologies and irrigation water consumers' decision-making processes. Usually, farmers frequently use irrigation to irrigate certain land areas while leaving others to be irrigated by rainfall. Studies have shown that the current wave of water-saving programs focuses mostly on engineering solutions, such as reducing seepage losses. However, adopting cutting-edge irrigation technologies is necessary to significantly improve on-farm WUE [136,139,149]. However, the adoption of technology is still a complex sociological phenomenon that greatly depends on people' willingness to adapt. Studies have highlighted irrigators' reluctance to commit to new practices or technologies since they must learn new abilities. The financial barrier to adopting new technologies and processes prevents their broad use [150]. Pressurized irrigation systems provide a greater WUE than surface irrigation, but they need a large initial capital investment and have higher energy expenses. Farmers are unable to fully utilize the technologies at their disposal to maximize WUE due to a lack of sufficient knowledge and incentives, which emphasizes the necessity of ongoing knowledge exchange among stakeholders. Though on-farm subsidies and infrastructure improvements have been used to improve WUE, their cost-effectiveness has occasionally been found wanting, leading to the exploration of other options such as water trading [139,151,152]. It is imperative to acknowledge the limited scope of WUE enhancement, particularly in systems that are currently functioning at nearly optimal levels. Studies have indicated that the benefits of technology advancements fade with time, emphasizing the necessity for ongoing attempts to develop new technologies that would further improve WUE.

7. Water Recycling Strategies in Arid Regions

Over 40% of the world's population will likely live in nations that are facing water shortages or stress in the next few years [153]. There are a number of factors that have contributed to this problem, including physical constraints and institutional challenges. In regions with limited freshwater resources, such as arid areas with unpredictable rainfall, effective water security requires careful and forward-thinking planning [154]. To address this challenge, it is necessary to explore the integration of alternative sources, such as recycled wastewater, into a diverse range of water supply options. This approach improves flexibility and adaptability while also reducing reliance on conventional sources. Water recycling is a highly promising solution that remains unaffected by climate variations. In addition, it provides various environmental benefits, such as reducing pollution in water bodies, preventing erosion caused by urban runoff, and minimizing the use of chemical fertilizers in agricultural irrigation [155]. The importance of water recycling is emphasized in the Sustainable Development Goal (SDG) target, which aims to achieve a global improvement in water quality by 2030. This includes reducing the proportion of untreated wastewater and significantly increasing recycling and safe reuse. Water recycling plays a crucial role in driving global sustainability initiatives. In regions with limited water resources, the need to ensure a sufficient and high-quality water supply to meet growing demands requires innovative solutions that involve diversifying water supply options and enhancing wastewater management.

AI-Based Industrial Waste Water Recycling

Through the use of computer systems, artificial intelligence (AI), which is also commonly referred to as machine intelligence, is able to imitate the activities of the human brain. It encompasses a wide range of fields, including cognitive linguistics, computer science, data science, and mathematics, among others [156]. Within the realm of wastewater treatment, artificial intelligence functions as a potent instrument that simplifies and streamlines procedures that are otherwise complex. The use of artificial intelligence for the treatment of wastewater has experienced substantial progress during the past few decades. It plays a significant part in a variety of tasks, including the prediction of treatment performance, the assessment of effluent quality, the optimization of operational parameters and unit designs, the development of sensors for component estimations, the

management of micropollutants, and the automation of maintenance methods [157]. Each intelligent control approach has both advantages and disadvantages, and in order to obtain the best possible outcomes, it is necessary to give serious consideration to the treatment system's mechanism and the reason for its existence. Research into the application of artificial intelligence models in wastewater treatment, which was carried out by using databases such as Scopus with keywords such as "wastewater treatment" and "Artificial Intelligence", indicates the changing landscape in this sector. Soft computing technologies, such as artificial neural networks (ANNs), are becoming widely utilized for the purpose of predicting water quality and related variables [158]. This is mostly owing to the fact that these tools are efficient, quick, and require less human participation. The use of artificial intelligence technologies, such as artificial neural networks (ANNs), fuzzy logic algorithms (FL), and genetic algorithms (GAs), is becoming increasingly prevalent in the monitoring of water treatment plant efficiency parameters [159,160]. These parameters include Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), as well as the elimination of nitrogen and sulfur, the prediction of turbidity and hardness, and the identification of contaminants in wastewater. According to previous studies, the removal of factors such as COD, BOD, heavy metals, and organics utilizing ANNs and hybrid intelligent systems can result in high determination coefficient values (up to 0.99) [158].

8. Use an Automatic Water Supply Facility

Automated water systems are essential for improving agricultural yields, maintaining landscapes, and replenishing vegetation in arid areas, particularly in times of limited rainfall [156]. In essence, they involve the regulated use of water on the land or soil. Nevertheless, the implementation of automated water supply systems faces obstacles, including a lack of knowledge about plant cultivation methods and limited familiarity with technology. In order to tackle these challenges, there is an increasing demand for a novel water delivery system that is simple to use and can be easily produced [154]. This system would provide multiple benefits, such as cost-effectiveness, user-friendly operation, low maintenance requirements, and energy efficiency. An issue often encountered with manual watering systems is the potential for over-watering, which can have a detrimental effect on plant growth. One possible solution is to implement automation by integrating moisture sensors that constantly monitor soil moisture levels. The water pump is activated solely when the soil moisture drops below a predetermined threshold, guaranteeing efficient watering without any unnecessary usage. This system is designed to function autonomously, activating the motor when the moisture content is below a certain level and mechanically deactivating it when the moisture level surpasses a predetermined threshold [157]. In addition, it incorporated GSM technology into the system, enabling users to remotely control the motor using their mobile phones [158]. Users can send commands to initiate or terminate certain processes, which will prompt the system to respond accordingly. The modem receives commands, cross-references the data with the microcontroller, and carries out the requested action [159]. In addition, this system offers immediate updates on its status, such as moisture levels, motor activation status, and user-sent commands. These updates are conveniently displayed on an LCD screen for effortless monitoring. One way to address these limitations is by incorporating GSM technology, which enables users to control pump operations remotely using mobile phone commands [160]. This feature offers convenience and flexibility, allowing users to easily manage irrigation schedules from any location. This helps to minimize the need for manual labor. To summarize, the creation of an automated water delivery system that utilizes moisture sensors and GSM technology presents a practical solution for optimizing water usage, improving agricultural productivity, and streamlining irrigation management in arid areas.

9. IoT-Based Accurate Irrigation

The cost of commercial sensors designed for agricultural systems and irrigation can be a major obstacle for smaller-scale farmers, preventing their widespread adoption [161].

There has been significant progress in the field, as manufacturers now provide cost-effective sensor solutions that can be incorporated into inexpensive irrigation management and agriculture monitoring systems. In addition, there is an increasing focus on the development of affordable sensors designed specifically for agricultural and water monitoring purposes [162]. These innovations consist of a leaf water stress monitoring sensor, a multi-level soil moisture sensor with copper rings arranged along a PVC pipe, a water salinity monitoring sensor with copper coils, and a water turbidity sensor using colored and infrared LED emitters and receptors. The progress made in these areas has the potential to make advanced monitoring technologies more accessible to a wider audience [163]. As a result of recent developments in sensor technology for agricultural irrigation systems, as well as the progression of technologies that are applicable to these systems, such as Wireless Sensor Networks (WSNs) and the Internet of Things (IoT), our objective is to provide a comprehensive overview of the current landscape of smart irrigation systems. Additionally, advanced irrigation systems where water is applied to the soil according to soil and climatic conditions, along with the installation of wireless sensor networks (WSNs) and Internet of Things (IoT)-based smart irrigation systems, can significantly im-prove water and nutrient use efficiency. This will enable smaller farmers to improve their agricultural practices and conserve water resources.

10. Conclusions

This review discusses various strategies to improve water-use efficiency (WUE) in agriculture, mainly focusing on agronomic methods such as crop selection, planting practices, moisture conservation techniques, and fertilization strategies. With the increasing challenges posed by climate change and water scarcity, it has become imperative for farmers to adopt sustainable agronomic practices to enhance soil health and crop resilience to ensure food security and promote environmental stewardship in the agricultural sector. Implementing agronomic practices that focus on enhancing soil health, improving nutrient content, and increasing antioxidant levels in plants can significantly contribute to the resilience of crops under water-limited conditions. Also, using phosphate-solubilizing bacteria and rhizobium inoculation are highlighted as effective methods to enhance WUE in agriculture. This review emphasizes integrating recycled wastewater, artificial intelligence in industrial wastewater treatment, automated water supply systems, and IoT-based accurate irrigation to achieve better water conservation and efficiency in arid regions. Additionally, a comprehensive overview of strategies like mulching, cover crops, canopy management, deficit irrigation, precision irrigation systems, and remote sensing is highlighted as effective methods for improving WUE. Also, maximizing the utilization of green water has been demonstrated to enhance plant transpiration demands, reduce excessive water flows, and improve agricultural productivity. These technologies provide real-time monitoring and data-driven insights that enable farmers to make informed decisions and adjust their irrigation practices according to changing weather patterns. Farmers can optimize their water usage effectively, conserve resources, and maximize crop productivity by utilizing such innovative technologies.

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