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

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Abstract: Water scarcity, particularly in arid and semi-arid regions, poses a significant challenge to crop production, with drought being a prevalent factor limiting grain production globally. Enhancing agricultural water use efficiency is crucial for managing water resources effectively in these areas. Water resource management involves planning, developing, distributing, and optimizing the use of water resources. Water use efficiency management is also essential for crop growth in arid regions. Various agronomic and irrigation strategies can improve crop water use efficiency and drought tolerance. The primary goal of these strategies is to maximize irrigation efficiencies by applying the precise amount of water needed to restore soil moisture to the desired level. These sustainable practices not only reduce the cost of water and labor for farmers through reduced irrigation but also optimize the use of soil moisture storage. This review paper explores practical techniques to improve water use efficiency, highlighting the role of nutrients in enhancing water use efficiency in crop plants.

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

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. (Davis et al., 2017). 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 (He et al., 2021; Islam & Karim, 2019). 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. (Kunzig, 2011), while the extraction of freshwater (which has already tripled since 1965) is growing at a rate of 64 km^3 per year (Lal, 2015). 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 (Prăvălie, 2016). This issue is most prevalent in Africa, the Middle East, and South Asia. (Gosling & Arnell, 2016). The enhancement of agricultural production and water use efficiency (WUE) in arid and semi-arid regions poses a significant challenge.

Deficit irrigation refers to the application of water below the required evapotranspiration level. (Chai et al., 2016). The water supply is reduced under deficit irrigation to meet the maximum evapotranspiration rate. (Fereres & Soriano, 2007). Automated irrigation systems schedule irrigation applications in real time based on soil water availability in the root crop zone. (Gu et al., 2020). This increases WUE by saving a significant amount of water. Deficit irrigation is a simple method to enhance economic output when water supply is limited. (Leite et al., 2015). However, various adjustments in the agricultural system are necessary due to the reduced water supply. The production of more food with less water can only be accomplished with better agricultural and agronomic management strategies that consider depleting aquifer conditions. Improving agricultural productivity and consumption of water has been taken into account as agricultural management of water (Kang et al., 2017). Climate change severely affects the water resources around several parts of the world including the Mediterranean, Europe, Central and Southern America, and Southern Africa. (Cramer et al., 2018). Climate change leads to increased runoff in water-stressed regions, such as Southern and Eastern Asia. However, this may not have practical benefits as the increased runoff occurs mainly during the wet season, and the additional water may not be accessible during the dry season. (Ogden et al., 2013).

WUE is commonly regarded as a crucial factor affecting crop yield under stress and as a component of crop drought resistance (Yu et al., 2020). The term "more crop per drop" has been used to suggest that rainfed plant production can be enhanced by maximizing the yield per unit of water utilized. The enhancement of genotypic transpiration efficiency (TE) and WUE primarily relies on plant traits that mitigate transpiration and crop water consumption, which are vital for plant productivity without genetic improvements in the biochemistry of photosynthesis. (Farooq et al., 2019). The primary focus for enhancing crop yield under drought stress is breeding for higher soil moisture retention. The concept of effective use of water (EUW) refers to the maximum uptake of soil moisture for transpiration while minimizing non-stomatal transpiration and soil evaporation. (Hatfield & Dold, 2019)Osmotic adjustment, a significant stress-adaptive trait in crop plants, is acknowledged for its ability to improve soil moisture retention and transpiration. (Blum, 2017). The high harvest index (HI) reflects the successful reproduction and yield of plants, as it measures the allocation of assimilates towards reproductive functions. Crop water deficit typically occurs during the reproductive growth stage in rainfed environments, decreasing harvest index HI. (Tavakoli et al., 2015). Furthermore, EUW enhances plant water status, enabling plants to withstand drought conditions.

Furthermore, efforts should be made to develop water and nutrient-efficient cropping systems that can enhance sustainability and agricultural productivity in drought conditions. Incorporating legumes into the cropping system is considered beneficial when combined with organic amendments like farmyard manure, poultry manure, and compost. (Abbott et al., 2018). This practice improves soil organic matter, soil structure, nutrient availability, and water retention capacity, leading to increased economic gains. (Murphy, 2015). Organic amendments efficiently recycle nutrients, enhance crop nutrient supply, improve water use efficiency, and serve as an alternative to synthetic fertilizers for improved farm production. (Kizito et al., 2019).

Improved WUE not only requires soil moisture conservation but also improved soil fertility among other crop production factors, simultaneously. Integrating practices with the ability to enhance soil fertility and conserve soil moisture is the most effective and sustainable approach toward enhancing soil WUE.

2. Strategies to Improvement WUE:

2.1. By Agronomic Methods:

The depletion of irrigation resources heightens the need to increase water use efficiency (WUE). Hybrid cultivars with improved WUE should be chosen under water-limited areas to increase water production per unit area. Many scientists (Awasthi et al., 2007; Behera et al., 2002; Chand & Bhan, 2002; S. Singh et al., 2004; Verma et al., 2003; Verma et al., 2001) have identified varieties of crops exhibiting higher WUE. These crops include wheat cultivars HUW 234 and Lok 1 for wheat, Vaibhav and SEJ 2 for mustard, and Varsha sorghum for sorghum. 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 (Sahadeva Singh & Bhan, 1998; Singh et al., 1998). 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 researches (Awasthi et al., 2007; Behera et al., 2002; Hira, 2004; Panda et al., 2004; Patel et al., 2008).

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 (Patil & Sheelavantar, 2000). 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,

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lowers erosion, and conserves moisture, it also improves water use efficiency (Singh et al., 2012). Especially in rainfed areas, intercropping protects against crop failure while diversifying cropping systems and optimizing water and resource utilization. Increased water use efficiency is a result of higher yields in intercropping systems, such as maize-soybean, maize-mungbean, and maize-potato, as opposed to mono-crops (Bharati et al., 2007; Goswami et al., 2002). 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 and green gram between paired rows of pigeon pea display better WUE (Kumar & Rana, 2007; Tetarwal & Rana, 2006). Furthermore, under various water conditions, particular intercropping combinations-like rice-lentil-maize+cowpea and rice-coriander-maize+cowpea-show greater water usage efficiency (Parihar et al., 1999; G. Singh et al., 2004). Crop geometry and row spacing optimization can improve yields and water usage 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 usage efficiency when planted with narrower row spacing and other alternative planting techniques, such as twin-row spacing (Jones, 2010; Karrou, 1998). In addition, studies conducted by (Patil & Sheelavantar, 2000; Rathore et al., 2008) showed that particular crop geometries-like sorghum planted in furrows or compartmental bunding-and row spacings-like 45 cm x 12 cm for bajra-help to maximize crop canopy and nutrient utilization, which in turn leads to increased water use efficiency. Chickpeas 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 (S. Singh et al., 2004). These results highlight the significance of crop geometry and row spacing in maximizing water use efficiency in agriculture.

Phosphate-solubilizing bacteria (PSB) and Rhizobium inoculation greatly increase legume crops' consumptive consumption and water use efficiency. In comparison to a single or no inoculation, combining Rhizobium and PSB inoculation in chickpea significantly boosts both variables (S. Singh et al., 2004). Singh et al. (2004) highlighted the importance of efficient weed control in raising water use efficiency by showing that weed-free treatments in chickpea production exhibit higher moisture use efficiency (M. Singh et al., 2004). Similar to this, Nadeem et al. (2007) found that manual weed treatment in wheat resulted in maximum water use efficiency, which was linked to decreased weed density and higher grain production (Nadeem et al., 2007). Furthermore, Reddy et al. (2008) discovered that pigeon peas grown under particular intercultivation techniques and herbicide treatments had higher water use efficiency, maybe as a result of decreased weed density and increased seed output (Reddy et al., 2008). Together, these findings highlight how crucial it is to optimize water use efficiency 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 (Kumar et al., 2000; Rathore et al., 2008). Raising nitrogen levels is associated with a significant improvement in water use efficiency in crops such as pearl millet (Kumar et al., 2003; Tetarwal & Rana, 2006). 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 (Abhijit Sarma et al., 2005; Behera et al., 2002; Ghosh et al., 2003; Parihar, 2004). 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 usage efficiency (Fangmeier et al., 2005).

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

2.2. Maximizing the Utilization of Green Water

Reducing the amount of water that precipitation deposits in the soil is crucial to 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 structure 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 wastes (Nguyen et al., 2013). 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 (Agnew et al., 2005; Agnew et al., 2002; Nguyen et al., 2013; Ross, 2010); (ii) weed control, which allows for a reduction in the amount of herbicide applied (Fredrikson et al., 2011; Steinmaus et al., 2008); (iii) prevention of soil erosion by improving soil structure and decreasing soil compaction (Agnew et al., 2002; Göblyös et al., 2011; Némethy, 2002); and (iv) increasing biodiversity, which can encourage beneficial insects to prevent pests (Huber et al., 2001; Thomson & Hoffmann, 2007). According to a study, using organic mulches improved yields while lessening the impact of disease and insects (Guerra & Steenwerth, 2012). Research on the effects of mulching on agricultural water uptake and retention, and consequently crop water use efficiency (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 (Gregory, 2004). These results align with certain reviews (Davies et al., 2011; Hatfield & Dold, 2019) 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 rate, 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 (Agnew et al., 2002). 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 is related to soil compaction (Némethy, 2002). Direct soil evaporation can account for up to 20% of water use, indicating that covered soil may improve plant water availability (Buckerfield & Webster, 2001).

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 to the wide variations in the impacts of mulching based on soil types, rainfall patterns, and evaporative demands (Jalota et al., 2001). That being said, different kinds of mulch may differ in their ability to retain water as well as in evaporative loss (McMaster, 2005).

2.3. 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 (Sarrantonio & Gallandt, 2003). Terrestrial ecosystems typically maintain a layer of plant residue on the soil's surface throughout the year, which affects seedling emergence and vegetation succession (Facelli & Pickett, 2010). 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 (Shanks et al., 2008). 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 (Hartwig & Ammon, 2012). 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 (Pou et al., 2011).

Numerous research have assessed the effects of Mediterranean legume-grass mixes as interrow cover crops on soil stability and crop performance (Lopes et al., 2004; Lopes et al., 2011; Monteiro et al., 2008; Monteiro & Lopes, 2007). 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 (Ingels et al., 2015; Wheeler et al., 2020). 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 (Monteiro & Lopes, 2007). Cover crops, however, clearly improve soil properties and alter the water dynamics in the soil profile (Celette et al., 2008). Pou et al. (2011) investigated the effects of several cover crops on plant development, production, quality, and water use efficiency (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 (Pou et al., 2011).

In summary, cover crops increase soil health, reduce erosion, and promote sustainable practices-all of which help to raise agricultural water use efficiency, or 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 crops have the potential to significantly increase WUE in agriculture, but addressing these challenges will need mindful planning and effective management strategies.

2.4. Canopy Management

Enhancing water use efficiency (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 (Carbonneau, 2021; Intrigliolo & Lakso, 2009; Medrano et al., 2012; Prieto, 2011; Williams & Ayars, 2005). 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 (Hatfield & Dold, 2019). Different plant species have different leaf arrangements, and transpiration rates are influenced by the canopy's structure, which influences solar radiation exposure (Michelon et al., 2020). Transpiration affects water consumption and is controlled by physiological and anatomical characteristics. Transpiration grows linearly with canopy leaf area, impacting dry matter production and photosynthesis (Xi, 2013). Photosynthesis and transpiration rates are influenced by mutual shadowing among leaves, especially in crops where the leaf area index (LAI) is higher than 4 (Hatfield & Dold, 2019). 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 4 (Ritchie, 1972; Sau et al., 2004; Villalobos & Fereres, 1990).

WUE substantially and positively depends on incoming light interception (Medrano et al., 2012). However, only a small number of research have concentrated on the impacts of the canopy on leaf gas exchange (Escalona, 2003; Intrigliolo & Lakso, 2009; Williams & Ayars, 2005) and WUE. Additionally, this study demonstrated that WUE was lowest on shaded leaves inside the canopy. 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 (Buckley et al., 2014). 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. 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 yield by 21% in cotton, it was able to reduce water use by 23% and improve output by 37% in wheat (Fan et al., 2018). Using a micro-irrigation system restricts practically all of the evaporation component from the canopy and lowers the amount of soil water evaporation from between plant rows early in the growing season (Fan et al., 2018; Hatfield & Dold, 2019). This shows that WUE can be altered by systemic water management and have a favorable impact on WUE in areas with irrigated crops. Research of Hatfield and Dold, (2009) explored the proper mechanism of canopy-level techniques to raise WUE in agricultural systems (Hatfield & Dold, 2019). Furthermore, Michelon et al., (2020) discussed the sustainable water management strategies for raising WUE in agricultural crop production (Michelon et al., 2020). By concentrating on factors like as leaf net photosynthesis and stomatal conductance, canopy management techniques, which include controlling crop water consumption and root system management, maximize water usage (Hatfield & Dold, 2019). Customized field management strategies improve agricultural water use efficiency even more and insure a productive and sustainable agricultural systems (Michelon et al., 2020).

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 to 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 evapotranspire (ETc.) (Yang et al., 2022).

This strategy has two variations:

I. Regulated deficit irrigation

I. Partial root zone drying

3.1.1. Regulated Deficit Irrigation:

It is based on the idea that a plant's susceptibility to water stress (quality, yield) varies during its phenological life. Thus, irrigation at lower amount than ETc. levels during particular times can significantly reduce vigour and enhance harvest quality while using less water (Chalmers et al., 2008; McCarthy et al., 2008). The This deficit irrigation method can be used to achieve various goals at various phenological stages, such as causing anthocyanin accumulation (Dry et al., 2010) or lessening the vigour of fruit cell division so its size (McCarthy et al., 2008). 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 (Yang et al., 2022). Excessive water reduction in this strategy, can cause severe yield losses and poor quality. on the other hand, excessive water can increase the vigour and so suppress the advantages of this strategy (Jones, 2004; Yang et al., 2022).

3.1.2. Partial Root Zone Drying:

Conversely, partial root zone drying involves wetting and drying approximately half of the plant root system in cycles of 8-14 days, depending upon 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 (Zhang et al., 2008). 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 (Medrano et al., 2015; Zhang et al., 2008).

4. Irrigation Modernization

Irrigation modernization implies the replacement of outdated irrigation infrastructure and procedures with current equipment and technology. Enhancing water conservation, streamlining

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water distribution systems, and reducing labour 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, save for routine maintenance and monitoring duties.

4.1. Water Distribution System

In Pakistan, irrigation has been a common longstanding practice. Pakistan's 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, Indus Basin Irrigation System (IBIS) has three main canals i.e. Right Bank Outfall Drain (RBOD), Left Bank Outfall Drain (LBOD) and Indus River itself. Only IBIS provide water to 8 million hectare land (Farid et al., 2019). Despite obstacles including unequal distribution and ineffective operations, this system guarantees water delivery to agricultural areas across the country (Gill & Sampath, 1992). Ongoing efforts aimed to increase its efficacy upon equitable water distribution and better management practices (Randhawa, 2002). Additionally, studies highlight how farmers compete with one another for water resources and how this affects agricultural productivity (Rinaudo et al., 2000). In Pakistan, irrigation system is 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 (Zakria, 2021). Precise flow monitoring is essential for improving Water Use Efficiency (WUE) because accurate water measurement is 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 (Moghazi & Ismail, 1997). 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 lining, the restoration of concrete and earthen channels, the installation of gravity pipes to replace open channels, and improvements to the irrigation infrastructure on farms (Randhawa, 2002). According to the proverb "You cannot manage what you cannot measure," so precisely measuring the water delivered to farmers is a crucial part of improving Water Use Efficiency (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 need, which is 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 (Jones, 2004). In Australia, tensiometers and soil probes are the irrigation scheduling tools that are most frequently used (Hornbuckle et al., 2009). Farmers that do not use scheduling software usually schedule irrigations based on past irrigation experiences. However, prior study suggests that these farmers, who rely on the "rule-of-thumb," might be losing water (Keen & Slavich, 2012). 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 (Gillies & Smith, 2005). 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 (Car et al., 2012). Even though there are proven benefits to using these technologies to improve WUE, there are still barriers to their application, including cost and complexity (Hornbuckle et al., 2009). 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 field scale. Most conventional irrigation methods aim to disperse water uniformly, which will produce a field-wide on-farm WUE that is similarly variable (Ahadi et al., 2013). 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 favour 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 get 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 (McClymont, 2007). 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 (Camacho et al., 2007; Khatri & Smith, 2006; Mailhol & Gonzalez, 1993). In a commercial cotton field in Queensland, Australia, a real-time optimization system for furrow irrigation was tested, and it showed lower labour costs and increasing WUE (Koech et al., 2014). The 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 (Uddin et al., 2018).

Thus, it is evident that real-time control and optimization, especially for surface irrigation, are still at its start even in irrigation sector of developed countries. However, considering the quantity of study and the advancements made thus far, it's 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 programmes 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 Water Use Efficiency (WUE) in irrigated agriculture depends on 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 (Jones, 2004). Furthermore, they are frequently site-specific, which restricts their use to wide areas. However, because of its ability to integrate with Geographic Information Systems (GIS) 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 (Ahadi et al., 2013; Nagler et al., 2013). WUE augmentation is aided by Landsat thermal infrared (TIR) images, which offers insights into ET regional variability (Anderson et al., 2012; Senay et al., 2016). 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 (Cozzolino, 2017). 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 getting 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 (Abbasi et al., 2014).

5.2. Communication Networking

Sensors are essential for collecting information about soil moisture and weather, which helps improve agricultural practices-particularly irrigation management. In the past, manual techniques involving cables were expensive and time-consuming, which resulted in errors in water management in the future. However, due to developments in technology and the availability of reasonably priced sensors, the use of wireless sensor technologies is expanding (Abbasi et al., 2014). A variety of field characteristics, including soil moisture and weather, can be monitored in real-time via wireless sensor networks, which are made up of sensor nodes and communication technologies (Abbasi et al., 2014; Cozzolino, 2017). 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 (Jawad et al., 2017; Ojha et al., 2015). By monitoring soil conditions and transmitting information via 3G networks, these sensors improve Water Use Efficiency (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 (Kumar & Ilango, 2018).

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 (Koech et al., 2018).

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 Water Use Efficiency (WUE), (Ruggiero et al., 2017) concentrate 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 (Roth et al., 2013). 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 (Rogers et al., 2016). (Tejero et al., 2011) discovered deficit irrigation techniques to improve WUE in a citrus crop experiment conducted in Spain. Similarly, (Du et al., 2015) promotes the use of deficit irrigation in China's water-scarce areas.

6. Water Consumption at Basin Scale

6.1. WUE and Water Consumption at Basin Scale

Water Use Efficiency (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 (Qureshi et al., 2011; Schaible & Aillery, 2012). What appears to be a loss in a basin context-such as deep drainage-might actually help groundwater recharge (Ahadi et al., 2013). Contrary to expectations, increased on-farm WUE can decrease downstream water availability or deplete groundwater (Qureshi et al., 2011). Expanded irrigated areas due to water-saving methods may result in higher water consumption at the basin size (Berbel et al., 2018; Molle & Tanouti, 2017). In Morocco, for instance, crop rotations and increased acreage caused by subsidized drip irrigation resulted in increased water use (Molle & Tanouti, 2017). Similarly, in India, the implementation of water-efficient techniques irrigation expansion while only partially reducing groundwater overextraction (Schaible & Aillery, 2012). Initiatives for groundwater recharge are one way to achieve a balance between efficiency and conservation (Plusquellec, 2009). But encouraging water-efficient technology on its own might not be enough to cut down on consumption of water overall (López-Gunn et al., 2012; Perry et al., 2017). Integrating incentives, rules, and conservation initiatives is necessary for effective measures (Perry et al., 2017; Schaible & Aillery, 2012). Furthermore, although pressurised irrigation systems improve productivity, they also use more energy and produce more greenhouse gas emissions (Ahmad & Khan, 2017). 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 (Expósito & Berbel, 2016). 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 WUE (Qureshi et al., 2011; White et al., 2006). 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 show that the current wave of water-saving programmes focuses mostly on engineering solutions, such as reducing seepage losses. However, adopting cutting-edge irrigation technologies is necessary to significantly improve on-farm WUE (Levidow et al., 2014; Qureshi et al., 2011; Roth et al., 2013). However, the adoption of technology is still a complex sociological phenomenon that greatly depends on people' willingness to adapt. Studies highlight 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 (Koech & Langat, 2018). 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 (Expósito & Berbel, 2017; Qureshi et al., 2011; Richards et al., 2013). It is imperative to acknowledge the limited scope of WUE enhancement, particularly in systems that are currently functioning at nearly optimal levels. Studies indicate 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 Region

Over 40% of the world's population would likely live in nations that are facing water shortage or stress in the next years (Zakar et al., 2020). 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 (Ilahi et al., 2021). To address this challenge, it is necessary to explore the integration of alternative sources, such as recycled wastewater, into a diverse range of

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water supply options. This approach improves flexibility and adaptability while 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 (Noor et al., 2023). The importance of water recycling is emphasized in 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.

7.1. Use 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 (Martínez et al., 2020). 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 (Ilahi et al., 2021). 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 (Sekaran et al., 2020). In addition, it incorporated GSM technology into the system, enabling users to remotely control the motor using their mobile phones (Kadam & Hwang). 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 (Adjardjah et al., 2022). In addition, the 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 (Bukola, 2020). 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.

7.2. 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 widespread adoption (Ndunagu et al., 2022). 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 (Ullah et al., 2021). 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 (Ahmad et al., 2022). 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

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systems, such as Wireless Sensor Networks (WSN) and Internet of Things (IoT), our objective is to provide a comprehensive overview of the current landscape of smart irrigation systems. It provide a summary of the most recent scientific developments in irrigation systems, with a particular emphasis on the parameters that are monitored, which include water quantity and quality, soil characteristics, weather patterns, and the application of fertilizer. That are utilized in the installation of wireless sensor networks (WSN) and Internet of Things (IoT)-based smart irrigation systems. This will enable smaller farmers to improve their agricultural practices and conserve water resources.

7.3. 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 (Vaishnav et al., 2023). 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 in 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 estimation, the management of micro pollutants, and the automation of maintenance methods (Khan et al., 2022). Each intelligent control approach has both advantages and disadvantages, and in order to get 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 (Chen et al., 2022). 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 (ANN), fuzzy logic algorithms (FL), and genetic algorithms (GA), is becoming increasingly prevalent in the monitoring of water treatment plant efficiency parameters (Ismail et al., 2021). 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 studies, the removal of factors such as COD, BOD, heavy metals, and organics utilizing ANN and hybrid intelligent systems can result in high determination coefficient values (up to 0.99) (Jana et al., 2022).

Conclusion

Improving agricultural water use efficiency will continue to increase because of the demand for increased grain production. Greater yield per unit of water is one of the most important challenges in water-limited agriculture. In plants, drought can cause a reduction in photosynthetic rate, chlorophyll content, stomatal conductance, transpiration rate, and relative leaf water content, and destruction of some physiological processes, ultimately reducing plant growth and development. An environmental stress like drought contributes significantly to reducing crop yields well below the potentially maximum yields, ultimately reducing WUE. Due to these risks, minimizing the detrimental effects of drought in plants below permissible limits is necessary.

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