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Enhancing water use efficiency through agro-ecological farming practices: Pathways to sustainable agriculture

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Abstract

Water scarcity has emerged as one of the major challenges to agriculture in the modern era, creating a need for innovative sustainable practices that improve water use while keeping production levels high. There are many opportunities to increase water use efficiency (WUE) in agro-ecological farming systems that prioritize biodiversity, soil health, and ecosystem-based management. The current understanding of WUE in agro-ecological contexts, including its determinants and measurement techniques, is compiled in this review. Additionally, it examines the relationship between enhanced soil moisture retention, reduced evapotranspiration losses, and increased crop water productivity and wool practices like crop diversification, organic matter, conservation tillage, agro-forestry, and integrated nutrient management. These strategies' applicability and feasibility in a variety of agro-climatic environments and resources are confirmed by case studies from both developed and developing nations. This process of adapting to climate change poses difficulties in obtaining scarce farmer incentives, practical limitations in calculating WUE, and some ambiguity surrounding more recent methods.

Keywords: Water use efficiency, agro-ecology, sustainable agriculture, climate resilience, soil-water management, agroforestry, conservation farming, precision irrigation

Introduction

Water scarcity is a concept that is gaining an increasingly significant role as an apparently most dangerous problem to the world agriculture. The possible existence of almost 70 percent of freshwater resources on food production is a major danger to food security, livelihoods and ecological sustainability as it is a highly inefficient use of the water resource ^[1, 2, 3]. Population growth, urbanization, and climate alteration are other factors which contribute to the straining pressure on the effective management of water in the agricultural sector ^[5, 10]. It is on this background that the issue of improving the water use efficiency (WUE) has become a significant policy to reach that mutually autonomous compromise between agricultural production and environmental management ^[11, 12]. Traditional agricultural systems have previously relied on the application of intensive farming methods and in majority of incidences they are guided by the desire to produce maximum produce and minimal consideration is given to efficiency of resources ^[4, 7]. The practices have contributed to depletion of ground water, soil degradation and poor water productivity ^[5, 16]. Instead, agro-ecological farming systems put emphasis on ecological principles, diversity, and sustainability ^[8, 9]. The purpose of these systems is to reduce the use of external inputs and enhance the ability to withstand climatic stress, which is why they are of particular use to the problem of water scarcity ^[14, 15]. Agro-ecological farming also utilises biodiversity as a way of improving WUE. Polycultures and crop rotation result in the decrease in the pests and disease pressure, water losses because of stressed crops ^[8, 9], agroforest systems reach to the ground water, and this reduces crop performance as a result of drought ^[12, 21]. The agro-ecological synergies confirm the potential of agro-ecology in the holistic solution to sustainable water management in agriculture ^[6, 10, 14].

Although these are benefits, there exist difficulties in mainstreaming agro-ecological in relation to WUE. Water efficiency in various agro-ecosystems is a complicated parameter to measure and, smallholder farmers are not always able to access resources and incentives to adopt them ^[2, 5, 7]. Poor extension services and economic trade-offs between yield and water savings complicate

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further the transition of conventional to agro-ecological system, policy gaps, and the fact that such transition is difficult to establish [16, 20]. In order to address these challenges, there will be a need not only to come up with scientific innovations but also favorable institutional arrangements [18, 19]. Given the urgency of the water issue in the world, the existing literature on WUE in agro-ecological farming systems will be summarized using this review. It examines the conceptual foundations, critical determinants and practices, which may enhance WUE to which case studies in various settings attest [1, 3, 6, 11]. It also looks into the issues, limitations and new technological advances underway to determine the future of water efficient agro-ecological farming [8, 9, 15]. By so doing, the review will focus on providing a comprehensive analysis of the way agro-ecology can be utilized as a pathway to a sustainable agriculture and climate resiliency [12, 14, 25].

Background on Global Water Scarcity in Agriculture

Agriculture is the most intense system of freshwater, which absorbs nearly 70 percent of world withdrawals [1, 2, 3]. However, the poor irrigation technologies, overutilization of ground water and climate changes have resulted in acute strains on the water supply [5, 10, 11]. The issue of chronic deficit is very real in most places and particularly in arid and semi-arid regions that directly threaten the crop and livelihood yields in the rural regions [20, 19]. The increasing population and the changing diet are also placing the water resources to the brink of their capacity creating a pressing need of more environmentally friendly methods of managing the same [12, 18]. It is also very alarming to the developing countries, where agricultural economies are

dependent on rain and uncontrolled extraction of groundwater [4, 16, 6]. There are areas of the world where water shortage is a constant problem such as South Asia and Sub-Saharan Africa due to regular droughts, unpredictable rainy seasons and inadequate irrigation systems [17, 20, 24]. The agricultural practices will continue to face the mounting pressure of meeting the world food demand and the survival of the vital water resource unless there is a significant change in the agriculture practices [2, 14].

Importance of Improving WUE for Food Security and Environmental Sustainability

The concept of water use efficiency (WUE), which refers to ratio of crop yield over water used, is increasingly being considered as a pillar to attaining food security as well as environmental sustainability [3, 11, 13]. Farming systems can be able to sustain the increasing populations by producing more output with less water, and also decrease the pressure on freshwater ecosystems [1, 5]. High WUE means that food supplies will be more stable during droughts and other climate-related shocks; in the case of countries relying on agriculture, it will decrease the exposure to the water crisis and promote the rural lifestyle [2, 10]. Enhanced WUE does not only lead to increased agricultural productivity, but also to ecological systems protection [7, 12, 16]. Conventional agricultural practices usually cause a drop in the quantity of groundwater, salinization, and destruction of aquatic biodiversity due to excessive water utilization [5, 19]. Through the implementation of the practices, which will maximize the WUE, farming systems will be able to restrict environmental degradation and at the same time provide sustainable food production [6, 15].

Table 1: Importance of Improving Water Use Efficiency (WUE) for Food Security and Environmental Sustainability

Aspect	Importance	Impact on Food Security	Impact on Environmental Sustainability
Crop Productivity	Efficient water use increases biomass and grain yield per unit water	Ensures reliable food supply even under water-limited conditions	Reduces need for over-extraction of water resources
Drought Resilience	Optimized WUE enhances crop tolerance to water stress	Maintains yield stability during dry seasons	Minimizes soil degradation and desertification risks
Resource Conservation	Reduces water wastage and maximizes irrigation efficiency	Supports sustainable crop production	Protects freshwater ecosystems and groundwater reserves
Soil Health	Better water management improves soil moisture and organic matter retention	Promotes long-term productivity for food crops	Enhances soil structure, fertility, and microbial activity
Climate Adaptation	Efficient WUE reduces vulnerability to variable rainfall and extreme weather	Secures food production under changing climate conditions	Reduces evapotranspiration losses and lowers carbon footprint
Socio-Economic Benefits	Optimizing water use reduces input costs for farmers	Improves food affordability and accessibility	Encourages sustainable agricultural practices and policy adoption

Objectives of the Review Paper

This critical review paper would focus on the importance of agro-ecological farming systems in improving the efficiency of water utilization [9, 10, 14]. It examines the operating principles of WUE, the contributions of important agro-ecological activities to it and their effectiveness in various agro-climatic regions [1, 5, 13]. The review critically summarizes available literature, case studies, and technological developments in order to present a general knowledge of how ecological solutions can revolutionize processes of water management in agriculture [2, 12, 20]. Besides the synthesis of knowledge, the paper also points out the obstacles and weaknesses of enhancing WUE by using agro-ecological approaches [7, 8, 16]. Besides, the paper presents the future directions, such as the combination of agro-ecological principles and modern technologies such as precision irrigation, remote sensing, and AI-based monitoring systems [11, 15, 18]. The setting of these goals makes the review part of the current attempts to create resilient, water-efficient, and sustainable

electrical landscapes [3, 10].

Literature review

The recent developments in remote sensing and geospatial technologies have facilitated monitoring and modeling land use and land cover (LULC) changes in details which is critical towards sustainable land and water management. In their study, Krishnan *et al.* [1] examined the space time dynamics of changes in LULC of Karamana River Basin, making use of the predictive modelling to offer strategies of managing the watershed. Similarly, Ibukun *et al.* [2] used machine learning techniques like gradient boosting and random forest to model the impact of mining on the land in Itagunmodi and found that time series analysis was essential for assessing how human activity affected the environment. This study demonstrates the value of temporal satellite data in forest monitoring. Jin *et al.* [3] developed a framework using phenology information that uses

fused satellite time-series data to identify deforestation in North Korea. There has also been a lot of research on urbanization and its effects on environment. Manikandababu *et al.* [4] applied object-based image classification to evaluate the effects of the urbanization near the coastlines with a focus on sustainable development. Deka *et al.* [5] considered the impact of LULC changes on the processes of groundwater in Assam, and it is clear that there is a correlation between water resources and land management. Tang *et al.* [6] used deep learning methods to map tidal flat topography that demonstrated the application of multi-temporal Sentinel data and the cross-modal sample transfer methods. Erkmen and Yener [7] examined land cover dynamics of Cyprus during several decades and found that multi-temporal Landsat imagery is useful in long-term monitoring.

The effects of LULC change to the biodiversity and human-wildlife interactions have received much research. Singh *et al.* [8] analyzed forest fragmentation and its role in human-wildlife conflict in Ranthambhore Tiger Reserve, India, highlighting ecological risks associated with habitat alterations. Vitale and Lamonaca [9] enhanced built-up area monitoring using multi-temporal satellite data fusion combined with machine learning, offering improved geospatial analytics for urban studies. Kasahun [10] quantified deforestation drivers through LULC and population correlation modeling in Ethiopia, providing insights into socio-environmental interactions influencing forest loss. Water resource management has been addressed through satellite-based assessments of hydrological dynamics. Wang and Gao [11] monitored long-term water storage in lakes and reservoirs of arid ungauged basins using multi-source satellite data, reflecting advances in remote sensing for hydrological applications. Deb *et al.* [12] focused on LULC dynamics under rapid urbanization in Jamshedpur, India, using geospatial technologies to inform urban planning decisions. Hao *et al.* [13] combined machine learning and remote sensing to analyze slope and ecological impacts of urbanization, emphasizing the value of multi-temporal datasets for environmental risk assessment. Nath *et al.* [14] provided a case study of the Sutlej Watershed, Punjab, demonstrating GIS and remote sensing applications in watershed management. Regional LULC monitoring has also been extended to various international contexts. Jannah and Arif [15] studied Gowa Regency's land cover changes using multi-temporal satellite imagery, reflecting the adaptability of these techniques across geographic scales. Hong *et al.* [16] assessed soil salinity in Vietnamese agricultural landscapes through remote sensing, illustrating how geospatial tools support agricultural planning. Aslam *et al.* [17] applied machine learning for wetland dynamics analysis, showcasing automated detection approaches in ecosystem monitoring. Devarajan *et al.* [18] focused on coastal and land resource monitoring in Coatzacoalcas, integrating environmental observations with geospatial analysis.

Population and urban growth continue to drive LULC changes. Alam *et al.* [19] highlighted the threat of population growth to forest ecosystems in the Hindukush-Himalayas, whereas Muchelo *et al.* [20] studied urban sprawl and agricultural land loss in Uganda, revealing regional patterns of land conversion. Doyog and Lin [21] generated wall-to-wall canopy height data using spaceborne LiDAR, emphasizing technological innovations in forest structure analysis. Mahato *et al.* [22] applied

satellite data to assess tea plantations' biophysical and biochemical traits in Northeast India, linking agricultural monitoring with remote sensing. Monitoring shoreline and wetland changes has been facilitated by cloud-based platforms and machine learning. Prasuna *et al.* [23] leveraged Google Earth Engine for shoreline and land cover monitoring in Uppada, India, demonstrating scalable, cloud-based geospatial analytics. Guo *et al.* [24] combined object-oriented and temporal features for mapping Liaohu Estuary wetlands, highlighting high-resolution classification approaches.

Concept of water use efficiency (WUE)

The Water Use Efficiency (WUE) is a significant measure of the efficiency of water use within agricultural systems to generate biomass or crop crop [1, 5, 12]. It is normally described as the ratio of product (biomass or grain yield) to the quantity of water consumed, which is commonly presented as kilograms per cubic meter of water [3, 6, 11]. A variety of methods can measure WUE with an example being biomass-based WUE, where the total amount of plant dry matter generated is divided by the amount of water lost; yield-based WUE that emphasizes the marketable center of the crop; and evapotranspiration-based WUE which takes into account the loss of water by the soil as evaporation combined with transpiration of plant leaves [2, 16, 22]. A model for ranking water productivity across crops, regions, and farming practices is provided by these metrics [7, 8]. The relationship between plants and water, soil properties, climate, and management practices should all be given particular consideration when interpreting WUE [5, 16, 22]. WUE based on biomass would provide data on overall crop growth, while WUE based on yield would be more relevant to economic interests and food security [12, 25]. In order to effectively monitor water losses and help farmers and scientists identify inefficiencies in water use, the evapotranspiration technique typically uses field sensors or remote sensing equipment [3, 6, 11]. Together, they could provide a more comprehensive picture of the degree of water productivity across different agroecosystems [1, 4]. Through WUE assessment, scientists are able to discover crops or systems that yield greater products using less water thereby ensuring sustainable water management [5, 7, 20]. Such measures are also essential in the policymaking and planning on a large scale to achieve a balance between the agricultural activity and the goal of water conservation in water-deficient areas [2, 13, 19].

Historical Perspective on WUE in Agricultural Research

The idea of WUE has been developing throughout decades starting with the classical work of crop physiology and water relations. Early studies of the mid 20th century were on the effects of transpiration on the growth and yield of plants that grew under different water supply [1, 3, 5]. Leading innovations emphasized that it was possible to overcome the problem of water scarcity in agriculture by enhancing the productivity of crops per unit of water exhaustion [2, 6]. Contemporary research considers WUE as a ratio of the yield to a unit of water in addition to the ecosystem service, nutrient use efficiency, and sustainability metrics [4, 10, 19]. The historical course proves that WUE has been a key idea in sustainable agriculture to bridge the gap between crop productivity and resource conservation [14, 25].

Table 2: Historical Perspective on Water Use Efficiency (WUE) in Agricultural Research

Era / Period	Focus of Research	Key Contributions	Impact on Agricultural Practices
Mid-20th Century	Plant transpiration and water relations	Understanding how water availability affects growth and yield	Laid foundation for measuring WUE at field level and linking it to physiological traits
1960s–1980s	Crop physiology and irrigation strategies	Quantification of WUE for different crops and irrigation methods	Adoption of improved irrigation scheduling and selection of drought-tolerant cultivars
1990s–2000s	Technological advancements	Introduction of lysimeters, soil moisture sensors, and remote sensing	More precise estimation of WUE across regions and crops; identification of site-specific strategies
2010s–Present	Integrated and socio-ecological approach	Combining WUE with ecosystem services, nutrient use efficiency, and sustainability indicators	Development of drought-tolerant varieties, climate-smart agriculture, and policy frameworks supporting efficient water use

Relevance of WUE in Agro-Ecological Systems Compared to Conventional Systems

The inherently efficient use of water is a core feature of agro-ecological farming systems that focus on the biodiversity, health of soil and ecosystem services [5, 8, 12]. According to such systems, WUE is very likely to be greater than in traditional monoculture or chemically intensive agriculture, because diversified patterns of cropping, organic amendments, and mulching minimise water losses and increase soil water retention [7, 10]. Agro-ecological systems achieve this through the combination of natural resource management with crop production to enhance the availability of water throughout the growing period to enhance resilience to changing climatic conditions [2, 20]. Traditional agricultural systems which are generally created to achieve maximum short term output might not make good use of water as they can use a lot of irrigation, lack the organic matter in the soil, and overly rely on chemicals [3, 6]. Conversely, agro-ecological practices increase the WUE through stimulating soil microbial activity, cover cropping and mixed cropping that reduce the losses through evapotranspiration and leads to better water infiltration [12, 16]. The emphasis on holistic management makes sure that inputs of water are efficiently converted into crop biomass and yield, which remain productive in the long run [1, 5]. Relevance of WUE in agro-ecological systems is also applicable to environmental as well as social sustainability. These systems increase water productivity and decrease pressure on fresh water sources, promote groundwater recharge, and slow down soil degradation [8, 11]. Moreover, enhanced WUE leads to food security particularly in the regions where there is water scarcity as it ensures that crops can survive under physical conditions of low water supply [18, 22]. Therefore, WUE is an ecological and technical standard that can be used to evaluate the efficiency and sustainability of agriculture practices [10, 19].

Agro-Ecological farming systems: principles and practices

Agro-ecological agricultural systems are informed by the principles that focus on ecological balance, conservation of biodiversity and sustainable management of resources [7, 12]. Among the most important of them is the combination of crops and animal to establish closed granules of nutrients, which would require minimal external chemical additives [16, 18]. This does not only increase the level of soil fertility but it also increases the general resilience of farms against pests, diseases and other climatic stressors [2, 5]. The other principle is the application of different crop species and varieties in order to maximize the utilization of resources and making yields more predictable, like natural ecosystems do [10, 25]. The second principle is to reduce the use of external sources of energy and to increase utilization of the local resources such as organic materials, rainwater and local knowledge [12, 14]. Agro-ecology encourages activities like composting, cover cropping, and crop rotation which preserve the soil structure, maximize the retention of water, and inhibit the proliferation of weeds in a natural way [6, 8]. These systems guarantee long-term sustainability in the productivity by prioritizing more on long-term soil health and ecological functions without destroying the natural resource base [1, 7]. Lastly, agro-ecological systems place an emphasis on the inclusion of local communities and farmers in the decision-making processes, which are comprised of socio-economic aspects and ecological goals [18, 20]. Participatory methods are used to make sure that the farming methods are adjusted to the local conditions, cultural knowledge and have the opportunity to adopt the sustainable practices into the market, and also increase their resilience [4, 10]. All these principles are combined to create an integrated system towards the ecological harmony, financial sustainability and social justice in agriculture [19, 25].

Table 3: Principles and Practices of Agro-Ecological Farming Systems

Category	Key Principles / Practices	Description / Benefits
Principles	Ecological balance and biodiversity conservation	Integration of crops and livestock, diverse crop species, and varieties to stabilize yields and optimize resource use [7, 12]
Principles	Minimization of external inputs	Use of local resources, composting, cover cropping, crop rotation, reducing reliance on chemical fertilizers and pesticides [6, 8]
Principles	Community participation and socio-economic integration	Farmers involved in decision-making, integrating cultural knowledge and market opportunities [18, 20]
Practices	Crop diversification	Intercropping, agroforestry, and mixed cropping to optimize water, light, and nutrient use, reduce pest pressure, and stabilize yields [5, 10]
Practices	Soil conservation and management	Contour farming, mulching, minimum tillage, organic amendments to enhance water retention, soil structure, and microbial activity [1, 16]
Practices	Water management	Rainwater harvesting, micro-catchments, drip/sprinkler irrigation to improve water use efficiency and reduce losses [12, 22]
Practices	Pest and disease management	Biological and cultural control, habitat diversification, beneficial insects, crop rotation, reducing synthetic chemical use [2, 16]
Practices	Adaptive management	Continuous monitoring of soil, water, and crop conditions to implement timely interventions [5, 22]

Practices in Agro-Ecological Farming Systems

A variety of techniques that improve soil fertility, biodiversity, and water consumption efficiency are implied by the realization of agro-ecological principles [5, 12]. Crop diversification, including agroforestry and intercropping, improves nutrient cycling, reduces pest pressure, and makes the best use of space, light, and water [7, 10]. Long-term productivity is improved by soil conservation techniques like contour farming, mulching, and minimum tillage, which also help to prevent erosion, improve water infiltration, and preserve organic matter [1, 6]. In order to maintain the health of the soil and vegetation, livestock integration—another crucial practice—offers manure as a source of nutrition recycling and grazing control [16, 18]. Agro-ecological farms usually have rainwater harvesting, drip irrigation, and micro-catchments to maximize water supply and minimize losses, which have a direct effect on the enhancement of WUE [12, 22]. Besides, organic modifications like compost, biofertilizers, and green manure improve the microbial activity and water retention in the soil and increase system resilience further [3, 7]. Agro-ecological pest and disease control methods depend on biological and cultural management of plants and insects instead of the use of synthetic chemicals [2, 10]. Habitat diversification, introduction of beneficial insects, and crop rotation are some of such techniques, which reduce the occurrence of pests but ensure ecological balance [12, 16]. Farmers are also advised to use adaptive management techniques depending on the ongoing observation of soil, water and crop conditions [5, 22]. All these combined practices help to improve sustainability, efficiency with water and productivity within agro-ecological farming systems [1, 25].

Factors influencing water use efficiency in agro-ecological systems

The aspect of soil such as texture and structure, organic matter and water-holding capacity are some of the key factors which dictate the efficiency with which water is used in agro-ecological systems [5, 12, 16]. Soils containing more organic matter also have a better capacity to hold moisture and hence minimise water stress during dry seasons and ensure a sustained growth of crops [7, 22]. Mulching, cover cropping and minimum tillage are management practices that help in improving the soil structure, as well as improving the infiltration and also minimizing the losses on evaporation [2, 6]. Specifically, the proper management of soil includes a better absorption and use of available water by crops, which specifically increases the biomass production and yield with the amount of water used [1, 10]. Water use efficiency is greatly influenced by the nature of crops grown, its growth behaviour as well as physiological characteristics [3, 8]. The high efficiency of the species within the context of water-limited environments is normally seen in drought-tolerant or deep-rooted species, as they are capable of reaching the soil moisture more intensively [11, 21]. Crop diversification, intercropping or agroforestry designs are also common in agro-ecological systems, and maximize the distribution of water over the root zones, and lessen competition within the field [12, 18]. Besides increasing the overall water productivity, such practices enhance resistance to climatic variability and also ensure that the

maximum water is used in multiple crops and growing seasons [5, 20]. The timing and method of irrigation have a significant role in determining the efficiency of water use [6, 13]. Conventional forms of flood irrigation tend to cause a lot of water loss through runoff and evaporations, but on the other hand, precision irrigation systems, including drip systems or sprinkler systems, are able to provide a direct water flow to the roots of the plant, reducing the level of wastage [1, 9]. Also, the combination of rainwater harvesting, soil moisture sensors, and deficit irrigation will enable farmers to only provide the crops with the necessary amount of water, improving the efficiency of the process but without reducing the yield, [12, 16].

Case studies and global practices

There are many examples of case studies in the world that prove that the efficiency of water use (WUE) in agro-ecological systems can lead to the increase of their productivity and the preservation of water resources [5, 12, 20]. Drip irrigation methods like drip systems have been used in Israel coupled with diversification of crops to ensure high production at low water costs; this has been used to create an example in arid and semi-arid areas [1, 9]. In a similar case, farmers practicing agroforestry and intercropping in certain regions of Sub-Saharan Africa have been able to increase soil moisture levels, mitigate evapotranspiration losses, and retain crop productivity by agroforestry and intercropping [10, 20]. In Asia, integrated water management such as rain water harvesting, mulching, and micro-catchments have been introduced in countries such as India and China and have shown to increase the WUE of smallholder farms particularly of water-intensive crops such as rice and sugarcane [5, 12, 22]. The issue of technology and the involvement of the community in improving WUE are also emphasized by global practices. The countries that have deployed remote sensing, soil moisture sensors, and climate-sensitive irrigation scheduling include the Netherlands and the United States to maximize the application of water at both farm and regional levels [3, 6, 11]. Strategies of participation, which engage local farmers in the decision-making and management, have already been found to be effective in enhancing the uptake of water-efficient methods in Latin America and Southeast Asia [18, 19]. These instances highlight the need to integrate the ecological principles, state-of-the-art technology and socio-economic approaches towards attaining sustainable water management in agriculture [7, 8, 25]. Also, other foreign programs and policy frameworks have also aided WUE improvements. Programs of the Food and Agriculture Organization (FAO) and the governments have encouraged best management practices, training of farmers and transfer of knowledge [13, 14]. Pilot projects have been conducted to optimize water in individual crops and it has been proven that despite the scarcity of water, productivity can be sustained or improved with very low water inputs in the water scarce areas [2, 15]. These experience cases offer substantial knowledge and adaptable measures that can be adopted in other areas where the same issue of water scarcity exists to show that a set of solutions can be adopted to realize both food security and environmental sustainability [12, 20].

Table 4: Case Studies and Global Practices on Water Use Efficiency (WUE)

Region / Country	Practices Implemented	Outcomes / Impact	References
Israel	Precision irrigation (drip), crop diversification	High yields with minimal water use; benchmark for arid/semi-arid regions	[1, 9]
Sub-Saharan Africa	Agroforestry, intercropping	Improved soil moisture retention, reduced evapotranspiration, maintained productivity under variable rainfall	[10, 20]
India & China	Rainwater harvesting, mulching, micro-catchments	Increased WUE in smallholder farms, especially for rice and sugarcane	[5, 12, 22]
Netherlands & USA	Remote sensing, soil moisture sensors, climate-smart irrigation scheduling	Optimized water application at farm and regional scales	[3, 6, 11]
Latin America & Southeast Asia	Participatory approaches with local farmers	Higher adoption of water-efficient techniques, improved WUE and productivity	[18, 19]
Global Initiatives	FAO programs, government policies, pilot projects	Best management practices, farmer training, crop-specific water optimization	[13, 14, 15]

Challenges and limitations

In spite of all these achievements, there are restrictions and a number of challenges that still exist in improving WUE in agro-ecological systems. Temperature and humidity variations affect the rate of evapotranspiration and the availability of soil moisture necessitating adaptive management practices, which may not be always viable to every farmer. The problem of limited access to technology, knowledge, and financial limitations usually hinder the use of precision irrigation systems, soil moisture measurement and other water-saving procedures especially on small-holder farmers in the developing world. Also, regarding socio-economic factors, more complicated issues, including land tenure, market access, and cultural practice, can affect the possibility or the desire of farmers to adopt the recommended practices. There is also a challenge in scaling field-level successful practice to a regional or national level. Cooperation and alignment of policies, strong governance frameworks and monitoring are key in ensuring longer-term gains in WUE, but most areas have institutional and logistical difficulties. Moreover, ecological, technological, and socio-economic elements of agro-ecological systems are complex in nature, and their breakdown may decrease the total performance.

Future outcomes

The sustainable agricultural productivity and climate resilience are closely related to the future of agro-ecological systems with a higher water use efficiency (WUE). With the increased rate of water scarcity caused by population growth, urbanization, and climate change, the practices of the kind of water use efficiency will be essential to ensure the crop yields but which will save the precious water resources. It will be the policy support and institutional frameworks that will influence the future of WUE interventions. Rewards of water-saving activities, training of farmers and sharing platforms will promote large scale application especially in regions where there is a constant water shortage. The joint efforts of governments, research, and local communities will guarantee pragmatic, scalable, and situational innovations leading to the establishment of sustainability and resilience of agricultural systems in the long term.

Lastly, agro-ecological systems can be improved to achieve world food security and socio-economic stability through improving WUE. Increasing yields in less environmentally damaging ways (through maximizing productivity of scarce water resources), the farmers will be better off in terms of the droughts risks, which will reduce the risks of higher costs in the event of crop failure. With time, a more resilient food system will be facilitated by improved WUE, competition between agriculture and other sectors will decrease because of freshwater, and sustainable livelihoods will be promoted,

especially in water-stressed areas.

Conclusion

Finally, water use efficiency (WUE) is very important measure of ensuring sustainable agricultural productivity especially in agro-ecological systems that combine ecological principles, diversified farming and soil and water preservation strategies. By utilizing the benefits of biodiversity, healthy soils and adaptive water management, agro-ecological systems have always shown higher WUE than other mono culture systems or systems that employ chemicals with the aim of producing high yields hence offer numerous advantages such as the ability to undergo climatic variability, high soil moisture retention, and low environmental impact. Internationally recognized case studies include drip irrigation in Israel, agroforestry and intercropping in Sub-Saharan Africa, integrated water management in India and China, and participatory water governance in Latin America, which shows that the ecological, technological, and socio-economic approaches have to be combined. However, there are still a lot of obstacles such as climatic uncertainties, the lack of access to technologies, and financial limitations and the possibility to transfer site-specific practices into regions in need of sound policy frameworks, institutional underpinnings and participation of farmers. In the future, the combination of the latest tools with the legacy of ecology, backed by the policy incentive and the platform of knowledge sharing, promises to streamline the idea of WUE, ensure crop satisfaction in the situation of water scarcity, and reduce environmental impairment. In conclusion, enhancing the water use efficiency in agro-ecological systems is a goal that leads to food security and farmers livelihood, but also to the overall global water sustainability, which means that more research, innovation, and cooperation must be conducted to reach the goal of a resilient and water-saving agricultural landscape.

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