International Journal of Advance and Applied Research
www.ijaar.co.in
ISSN – 2347-7075 Impact Factor – 8.141
Peer Reviewed Bi-Monthly
Vol. 6 No. 19 March - April - 2025

Sustaining the Future: Water Conservation Strategies for Sustainable Agriculture

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DOI - 10.5281/zenodo.15148258

Abstract:

Agriculture requires water as its inherent source, accounting for approximately 70 % of freshwater withdrawals. Climate change exacerbates water scarcity, and increasing demand for food production necessitates agricultural conservation through sustainable means. This article discusses new and practical steps to improve water efficiency and conserve water for long-term farming sustainability. The technologies include sprinkler and drip irrigation, which maximizes water application to plants while minimizing evaporation and runoff. Besides, the using soil moisture measuring equipment and decision-making using data enhances efficiency in crop-based irrigation scheduling for maximum water saving. Another key strategy is using drought-resistant crop varieties and agroecological practices, including crop rotation, intercropping, and conservation tillage that improve soil health and water-holding capacity. Rainwater harvesting and on-farm water storage structures are essential for capturing and storing rainwater and minimizing reliance on groundwater and surface water supplies. Mass acceptance will also require a policy that supports water-saving technologies and controlled water resources. The development and use of sustainable water management are highly reliant on collaboration among stakeholders like farmers, researchers, policymakers, and entrepreneurs. A likely starting point would be to launch an education and awareness campaign for these conservation practices and instil a conservation culture. Agriculture can balance sustainability and productivity by embracing technological innovation, ecological approaches, and policy measures to safeguard water resources for future generations. This will solve present-day water challenges and enable long-term environmental and food security targets, sustaining agriculture to be resilient in the future.

Keywords: Climate Change; Sustainable Agricultural; Water Conservation; Irrigation Technology

Graphical Abstract:

Introduction:

Sustainable farming requires efficient water-saving methods to avoid the impacts of water shortage and greenhouse effects that are imperative in maintaining sustainable farm production and sound ecosystems. Precision agriculture has emerged as a significant method, utilizing technologies like IoT, remote sensing, and smart irrigation to optimize water use and improve the real-time observation of the ecosystem to improve crop resistance and resource utilization efficiency in arid environments. Conservation agriculture (CA) also ensures sustainability through minimum soil disturbance, permanent soil cover throughout the year, and rotation, resulting in healthier soil and water conservation. New drip and sprinkler irrigation systems must maximize water use efficiency as they conserve water and increase crop yield and productivity (Fig. 1). New hydrogel soil water retention technology and solar-powered irrigation pumps are becoming popular with clean alternatives to conventional practices [1]. Supporting the traditional methods with these technologies, policy support, and people's participation is crucial to making water conservation in agriculture easier. In addition, water-saving agriculture practices such as crop rotation, integrated pest management, and conservation tillage reduce water consumption and preserve natural resources, promoting biodiversity and environmental sustainability. However, financial constraints, technological adoption barriers, and the need for drastic policy and consumer attitude shifts must be addressed to unleash the full power of these approaches. An integrated strategy should synergistically integrate technology, policy, and people's participation to support agricultural water conservation and ensure that it is sustainable and resilient to different environmental and socio-economic challenges [2], [3].

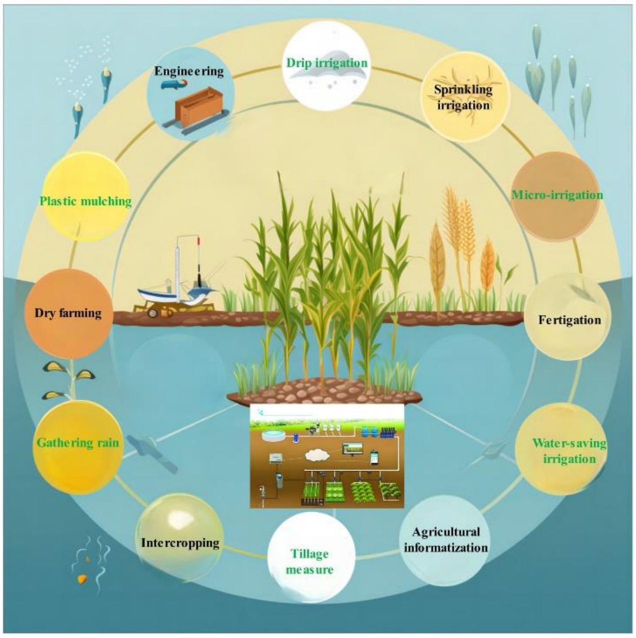

Figure 1: Improve water resource utilization efficiency and reduce agricultural water use through water-saving technology to ensure crops grow and develop generally under limited water resources.

Water, the planet's blood, is increasingly becoming a precious resource. Essential to all aspects of life, its use in farming is of supreme importance. Farming, tilling of the soil, and raising animals and plants are the pillars of human society, nourishing and stimulating economies worldwide. However, this vital sector has one fatal flaw: its massive dependence on freshwater. Agriculture consumes almost 70% of all freshwater drawn globally, a mind-boggling figure that shows the sector's vulnerability to drought. Agriculture must transform with global warming enhancing stresses and the world's population expanding exponentially. We must move towards a more sustainable approach that emphasizes water conservation and ensures that the world's water resources and agriculture are sustainable in the long run. The issue is complicated [4]. Climate change exacerbates water scarcity in most of the globe, creating more intense and frequent droughts. Warming increases evapotranspiration and water loss from soil and plants to evaporation and transpiration, further depleting water resources. Meanwhile, the planet's population continues to grow, causing food demand to be higher. That demand and evolving diets put enormous pressure on-farm production to extract more from potentially less. Integrating all these aspects is a formula for disaster, risking food safety and livelihoods for millions around farming. Conventional farming systems that depend on the non-optimal consumption of water and water-hungry crops do not work in such a scenario. Excessive watering wastage due to evaporation, runoff, and inappropriate application are issues to be highlighted. Apart from this, groundwater and surface water resources diversion for irrigation and aquifer drawdown of groundwater result in environmental degradation and threaten other vital uses' water supply. It just cannot go on like this. We must embrace innovation and move towards environmentally sustainable solutions for reducing water losses, enhancing water productivity, and enhancing agricultural system resilience to climate change and rising demand. The article follows the call to save water in agriculture to the areas of new and varied alternatives with the potential to save water in this industry. It discusses the possibility of applying accurate irrigation technology, such as drip and sprinkler irrigation, which delivers water directly to the plant roots and avoids evaporation and run-off loss. The importance of data-based irrigation scheduling with soil moisture-monitoring technology and real-time feedback to plan the water application based on the actual crop requirement is also highlighted. Further, the role of drought-resistant crop varieties and agroecological management practices such as rotation, intercropping, and conservation tillage are discussed in improving the soil and higher water holding capacity. These practices save water and render farms resilient and sustainable [4], [5]. Besides on-farm management, the article also finds relevance in the context of rainwater harvesting and on-farm water storage facilities. Rainwater harvesting and utilization can reduce reliance on groundwater and surface water resources and raise local water security and conservation. Moreover, how policy and incentives are used to encourage water-saving technology and water resource management in an integrated way are also discussed. It is essential to have a facilitating policy environment to encourage farmers to adopt sustainable agriculture practices and invest in water-saving technology. Finally, the article also highlights stakeholder cooperation and public awareness activities [6], [7].

It will require the whole effort of farmers, industry, policymakers, scientists, and society to be in a position to eliminate water shortages in agriculture. Public awareness and education are vital in establishing the culture of water conservation and helping people make the correct decisions regarding water use in agriculture and other uses. The future of agriculture is dependent on our ability to adopt sustainable water management. By embracing technological advancement, environmental science, and policy incentives, we can construct a strong and sturdy agriculture system that can respond to rising food demand without the cost of our precious water resources for future generations. It is not only a short-term approach to tackling water scarcity. Still, it ensures far-sighted environment and food security targets, setting up agriculture as a pillar of human civilization over the next generations. The water-secure agro-future pathway appeals to everybody to hold hands and transform, the ability to take up change, and the shared recognition of water as the central turning point for continuing life and living [7], [8], [9].

1. The Challenge: Agriculture and Water Scarcity:

The water and agriculture dependence are reciprocal but progressively restrictive. Agriculture, the world pillar of support for food production, relies on freshwater. Approximately 70% of all freshwater extracted from the environment goes to irrigation, an indicator of the industry's colossal dependence on valuable resources. Such reliance, however, is progressively precarious due to various factors, mostly water shortages and the effects of climate change. Physical and economic water scarcity is growing in most parts of the world. A physical shortage occurs because the water demand exceeds its supply. Conversely, the economic shortage arises from a shortage of infrastructure or the means of procuring and utilizing water resources. Global warming is responsible for such deficiencies by altering the rainfall pattern, increasing the occurrence and severity of droughts, and impacting surface and groundwater supply levels [10]. The increased temperature also accelerates by promoting evapotranspiration, land evaporation, and plant transpiration, further removing water from the crop. Simultaneously, the world continues to have an increasing population with higher demand for food, and an enormous burden is placed on the food system to produce more and perhaps fewer inputs. This dynamic of forces poses a core challenge: sustainably feeding a growing population while maintaining and conserving declining water resources. Traditional farming methods, usually flood irrigation and other water-wasteful techniques, are no longer an option here. These methods are predisposed to create unwarranted water loss by evaporation, runoff, and deep percolation, draining already strained water sources. Ending this issue requires a dramatic shift towards more water-saving farming and appreciating the interconnectedness of water security, food security, and environmental sustainability [10], [11].

Table 1: Challenge and Description of Agriculture and Water Scarcity

Challenge	**Description**	Ref.
Physical Scarcity	Insufficient water due to environmental conditions, such as low rainfall and arid climates, leads to droughts and reduced water availability for agriculture.	[10]
Economic Scarcity	Inadequate water infrastructure and management, often exacerbated by governmental negligence, leads to inefficient water distribution and increased stress on water resources.	[8]
Climate Change	It Alters precipitation patterns, increases drought frequency, and causes glacier melting, further exacerbating water scarcity and impacting agricultural productivity.	[7]
Agricultural Demand	Agriculture consumes approximately 70% of global freshwater, with inefficient irrigation practices leading to significant water wastage and increased scarcity.	[9]
Technological and Management Solutions	Adopting remote sensing, AI, and improved irrigation techniques can enhance water use efficiency and mitigate scarcity.	[12]
Policy and Institutional Challenges	Lack of effective policies, investment in water infrastructure, and poor management exacerbate water scarcity issues, necessitating comprehensive policy reforms.	[10]
Socioeconomic Impacts	Water scarcity threatens food security, reduces agricultural productivity, and increases the vulnerability of marginalized communities, necessitating integrated management strategies.	[7]
Global and Regional Variability	Water scarcity impacts vary globally, with regions like Asia and China facing significant challenges due to high agricultural demand and uneven water distribution.	[12]

2. Precision Irrigation Technologies:

Precision irrigation technologies offer a new water management method in agriculture, moving away from traditional and wasteful mechanisms to optimized and precise water delivery. Precision irrigation technologies maximize water use efficiency by delivering water precisely at the plant roots, minimizing loss due to evaporation, runoff, and deep percolation. Sprinkler irrigation and drip irrigation are two perfect examples of precision irrigation. Drip irrigation, or micro-irrigation, is slow water release through a network of tubes and emitters onto the plant stem. The process delivers water where needed, with reduced water loss and reduced opportunity for weeds to grow. Drip irrigation is best adapted to high-value crops and dry or semidry locations where water is at issue. Otherwise, Sprinkler irrigation refers to water supply through a sprinkler or sprayer system that simulates natural rain. Although less precise than drip irrigation, sprinkler irrigation is still likely to be far more efficient than flood irrigation, provided it is well-planned and well-operated [1], [2]. Variable irrigation in contemporary sprinkler systems adjusts the water application rate based on site conditions and soil type. Also, with the integration of sensors and data analytics, monitoring and managing irrigation systems in real-time is possible, further increasing and conserving water usage. Precision irrigation technologies are a key move towards sustainable agriculture because they enable farmers to produce more using less water and conserve this precious resource [12], [13].

3. Data-Driven Irrigation Scheduling:

While precision irrigation technology guarantees efficient water delivery, optimal scheduling of irrigation is also required to achieve optimal water use efficiency. Data-driven irrigation scheduling uses real-time data and analytics to decide when and how much water crops need. It moves from such estimation or calendared-based scheduling duties to a more scientific and reactive approach. Some of the technology and instruments utilized in data-driven irrigation scheduling are Soil water content at various depths, real-time readings, and soil moisture sensors, whereby actual crop water status is available to farmers. Weather stations and weather forecasts provide temperature, humidity, rainfall, and evapotranspiration data, whereby the farmers can estimate crop water demand and irrigate according to scheduled plans. In addition, remote sensing technology, such as aerial photography and satellite imagery, can capture vital information on crop health and water stress to a large spatial extent. Once this information is incorporated into sophisticated decision support systems, farmers can make more informed scheduling choices on irrigation, where they can maximize the application of water to actual crop needs and prevent wastage. By using data-driven irrigation scheduling, farmers are conserving water, enhancing crop quality and quantity, and achieving economic and environmental sustainability. It is one step towards precision agriculture, in which technology and information improve all facets of crop growth, including irrigation [6], [7].

Drought-Tolerant Crops and Agroecological Practices:

Agroecological methods and drought crops are promising solutions to attaining water saving to its full capacity in agriculture over saving water and practicing efficient irrigation side by side. Both of them can be labelled as "water-wise crops." They entail crops developed or specially cultivated as water deficiency tolerant to withstand and produce high yields even with unfavorable dry conditions. They usually have physiological traits that enable them to access water from the soil more, conserve transpiration water loss, or survive on less water. Farm crops that are drought tolerant can significantly reduce irrigation water requirements for a whole region, especially in arid and semi-arid areas. Besides that, agroecological management is planned to mimic the natural ecosystem to maintain the sustainability of agriculture and establish a significant role in soil health maintenance and water storage. Cropping rotation, intercropping, and conservation tillage assist in building soil organic matter, enhance soil's physical structure, and encompass water infiltration and storage capacity. Crop rotation is the sequential replacement of different crops in a given field over time, which enhances soil health, reduces pest and disease issues, and enhances water use efficiency. Intercropping, or planting two or more crops simultaneously in a single field, can enhance water and nutrient uptake, reduce erosion, and provide superior farm biodiversity. Conservation tillage, which limits soil disturbance using techniques such as no-till farming, saves soil water, minimizes erosion, and increases the soil's overall health. Farmers can produce more drought-resistant and water-saving farming systems by integrating agroecological techniques with drought-resistant crops and making them more drought-resistant while increasing long-term sustainability [8], [9], [10].

Rainwater Harvesting and On-Farm Water Storage:

Rainwater harvesting and on-farm water storage are decentralized and environmentally friendly methods of augmenting water supply to agriculture. Rainwater harvesting entails the capture of rainwater from rooftops, pavement, or other runoff surfaces and storing it for subsequent use. Collected rainwater can be used to water animals, for irrigation, or other farm uses, relieving reliance on groundwater and surface water sources. Ponds, reservoirs, or tanks provide on-farm water storage structures that store harvested rainfall or runoff field water to maintain dry seasons. The infrastructure could be convenient in dominant rain season areas where water is trapped and held from rainy periods to dry seasons. Rainwater collection and the on-farm storage system help add farm-level access to the water supply, restore the groundwater base, and avoid excess pressure on the centralized systems. Such systems can benefit smallholder farmers in remote areas with limited irrigation infrastructure. Rainwater harvesting and on-farm storage increase agricultural water security and resilience by allowing farmers to manage their water resources [1], [14], [15].

Policy and Incentives for Water Efficiency:

New technology and water-saving agriculture are central to conserving water, but policy and incentives also enter into the picture to ensure universal adoption (Table 2). Governments must be leaders in encouraging an environment that fosters water-saving agriculture through several policy instruments. These can involve water use limitations, pricing mechanisms aligned with the actual cost of water, and rewards for water conservation practices and technology. For example, governments can provide subsidies or funding to farmers to purchase precision irrigation equipment, rainwater harvesting systems, or any other water-saving equipment. They can implement pricing of water that encourages conservative usage and does not encourage wasteful consumption. Besides this, policies to ensure holistic management of water resources in terms of interlinkages between surface water, groundwater, and rainwater are required for the optimal use and allocation of water. With a policy framework enabling water efficiency and effective water use, governments can speed up the process towards water-secure agriculture [1], [2].

Table 2: Synthesizes various policy and incentive strategies for enhancing water efficiency, drawing from diverse contexts and implementations across different regions and sectors. Each approach is tailored to specific challenges and opportunities, demonstrating the multifaceted nature of water management policies.

Policy/Incentive Type	Description	Examples/Implementation	Outcomes/Benefits
Water Pricing Policies	Economic instruments such as water pricing manage water demand by increasing prices while providing subsidies to encourage efficient irrigation technologies.	A genetic algorithm-based optimization model was used to simulate water pricing policies, resulting in a 40% increase in net benefits, amounting to US$249.3 million annually	Improved water use efficiency and increased economic value of water [3], [13]
Cooperative Agreements (CAs)	Voluntary agreements and payments for ecosystem services (PES) schemes supplement existing regulations to promote water efficiency.	Implemented in regions like Dorset (UK), Evian (France), and New York (USA) to improve water quality and river restoration in Ebro (Spain)	Enhanced water quality, environmental and social outcomes, and effective policy implementability [3].
Incentive Regulation	Incentive schemes improve efficiency in water utilities by reducing non-revenue water and increasing energy efficiency.	Tariff incentive mechanisms in Passos and Itabira, Brazil, and incentive-stacking in Southern California	Increased billing efficiency, reduced water losses, and improved energy efficiency [1]
Market-Oriented Mechanisms	Governments compensate irrigated agriculture for reducing water diversions to augment environmental flows.	In the Murray-Darling Basin, Australia, policies include paying irrigators for investments in irrigation and conveyance or buying water from irrigators.	More considerable return flow reduction and significant reductions in consumptive use [1]

1. Stakeholder Cooperation and Public Awareness Campaigns:

Agricultural water scarcity issues must be resolved by concerted action from all stakeholders every quarter. Scientists, policymakers, farmers, business owners, and civil society players must all contribute to saving and responsible water use. Stakeholders must unite, exchange information, develop innovative methods, and apply effective policies. Apart from the above, public education programs are needed to raise farmers' and the public at large's awareness of the importance of water conservation in agriculture and the benefits of using water-saving techniques. Such public information campaigns may employ various forms of communication, such as workshops, demonstrations, mass media, and the internet, to disseminate information and sensitize people towards water-saving commodities, best buys, and reasonable water utilization. Encouragement of water-saving culture, allowing the public to make decisions for responsible water usage, cooperation among the various stakeholders, and public sensitization campaigns will go a long way in adopting sustainable water usage in agriculture [16], [17].

2. Integrating Technology, Ecology, and Policy:

A prosperous agricultural future is within grasp by integrating technological progress, environmental principles, and enabling policies. Technology provides the instruments and mechanisms for enhancing water use efficiency, from precision irrigation technology to soil moisture sensors and remote sensing technologies. Ecological principles are the basis for understanding the complex interplay between agriculture and the environment in which soil well-being, diversity, and ecosystem services are advanced as a requirement. Support policies encourage a regime in which incentives, regulation, and water stewardship guidance make it easier to adopt sustainable approaches. All three pillars of technology, ecology, and policy collectively can construct a resilient and sustainable agri-food system that meets growing food needs without undermining our precious water resources. It is an integrated process that realizes that water saving in agriculture is no less a social, economic, and environmental issue as it is a technical process [18], [19], [20].

Conclusion:

Our capacity to adopt sustainable water management concepts is the key to the future of agriculture. Water scarcity, driven by climate change and food overconsumption, is a monolithic risk to global food security and the livelihoods of millions relying on agriculture. However, we can introduce an agriculture-saving water and resilient sector through an integrated policy response with a bias for technological advancement, green thinking, and facilitation. Precision irrigation, data-based water scheduling, water-efficient crops, agroecological management, rainwater harvesting, and farm storage are the key instruments to enhance water efficiency in agriculture. Supportive policies, stakeholder collaboration, and public awareness campaigns are also necessary to promote the mass adoption of these water-saving measures. By adopting these integrated strategies, we can ensure agriculture becomes a food source for the increasing population and secure our planet's precious water resources for the coming days. A transition to this direction of water security and future sustainability in agriculture necessitates unflinching reciprocal commitment towards alteration, an awareness of innovation, and the same realization about the role of water in existence and lifestyle. This path involves collaboration for the above reason by global efforts in partnership through coordination among farmers, scientists, decision-makers, and buyers towards accomplishing a stage in which water and food security reciprocate mutually and co-insistently reinforce.

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