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Advancing Water Conservation Techniques in Agriculture for Sustainable Resource Management: A review

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ABSTRACT

The evolution and impact of water conservation techniques in Indian agriculture, underlining their vital role in fostering sustainable resource management amidst increasing global water scarcity. It begins by exploring traditional water management practices, illuminating their historical relevance and the constraints they face in meeting contemporary agricultural demands. The focus then shifts to modern water conservation methods, including technological advancements in irrigation, such as drip irrigation, sprinkler systems, and subsurface irrigation, alongside agronomic practices like crop rotation, soil moisture management, and mulching, which collectively enhance water efficiency. It explores into the crucial influence of technology and innovation in Indian agriculture, spotlighting precision agriculture with a particular emphasis on sensors and IoT for water management, remote sensing, satellite imagery, and data-driven methodologies incorporating AI, machine learning, and decision support systems. Additionally, it investigates cutting-edge solutions like hydrogel technology for soil water retention and solar-powered irrigation systems. The review also addresses the significance of supportive policy frameworks, community-oriented water management strategies, and the role of education and awareness, highlighting government initiatives, international collaborations, NGO involvement, and farmer training programs. Regional case studies are presented to analyze the effects of these water conservation practices on sustainability and productivity, offering insights into lessons learned and the potential for replication. Lastly, the review identifies and discusses the challenges and barriers to implementation, encompassing economic and financial limitations, technological and infrastructural gaps, social and cultural obstacles, and environmental considerations. Ultimately, this review emphasizes the need for a holistic approach that synergistically integrates technology, policy, community engagement, and education, crucial for advancing water conservation in Indian agriculture and ensuring its sustainability and resilience amidst diverse environmental and socio-economic challenges.

Keywords: Irrigation; sustainability; technology; conservation; innovation; community.

1. INTRODUCTION

India's agricultural sector, a cornerstone of its economy, heavily relies on water as a critical input. However, the country faces significant challenges in water management, primarily due to its vast and diverse geographical expanse and burgeoning population. Agriculture in India consumes about 80-90% of the total water resources, making it the largest user of water [1]. This intense dependency on water resources for agriculture is juxtaposed with a growing crisis of water scarcity. A report by NITI Aayog (2018) highlighted that 21 major cities, including New Delhi, Bengaluru, and Chennai, are racing towards zero groundwater levels, affecting access for 100 million people. The situation is exacerbated by climate change, which is altering rainfall patterns and exacerbating water scarcity [2]. In this scenario, water conservation in agriculture is not just a necessity but a critical measure for the survival of millions who depend on agriculture for their livelihoods. Globally, sustainable resource management has gained paramount importance as it directly correlates with the survival and health of ecosystems and human populations. Sustainable resource management in agriculture, particularly in a country like India, involves optimizing water use, ensuring that the needs of the present are met without compromising the ability of future generations to meet their own needs [3]. The concept is vital in the Indian context due to the country's large population, which is expected to surpass China's by 2027, making India the world's most populous country. This demographic trend puts immense pressure on its natural resources. Sustainable water management in agriculture is crucial for India to achieve several United Nations Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 12 (Responsible Consumption and Production). The purpose of this review article is to provide a comprehensive analysis of the advancing water conservation techniques in India's agricultural sector and their role in sustainable resource management. This article aims to explore various traditional and modern water conservation practices, the integration of technological innovations, the implications of policy frameworks, and the involvement of community and educational initiatives in fostering sustainable water management in agriculture. While the focus is predominantly on India, the insights and findings from this review can offer valuable lessons and strategies applicable to other regions facing similar challenges. The scope of this article encompasses an examination of both the successes and challenges faced in implementing water conservation techniques in India's agricultural sector, thereby providing a nuanced understanding of the complex interplay between water management, agricultural productivity, and sustainable resource development.

2. THE NECESSITY OF WATER CONSERVATION IN AGRICULTURE

The urgency for water conservation in agriculture is underscored by the escalating crisis of global water scarcity, which profoundly impacts agriculture, especially in countries like India. Agriculture, being the largest consumer of water globally, faces significant challenges due to diminishing water resources, a situation aggravated by climate change. According to the World Resources Institute (WRI), India ranks 13th among the world's 17 'extremely water-stressed' countries, indicating a severe imbalance between water demand and supply [4]. This scarcity is not just a rural phenomenon but also affects urban areas, often leading to conflicts over water resources. In agriculture, water scarcity translates to reduced crop yields, affecting food security and livelihoods, particularly in agrarian economies [5]. The Food and Agriculture Organization (FAO) reports that water scarcity can lead to a decline in agricultural productivity by 10-30%, posing a grave threat to food security. The role of agriculture in water usage in India is pivotal, with the sector accounting for more than 80% of the country's freshwater usage, a figure significantly higher than the global average of 70% [6]. However, this also implies that agriculture holds substantial potential for water conservation. Efficient irrigation practices, such as the shift from traditional flood irrigation to micro-irrigation techniques like drip and sprinkler systems, can considerably reduce water wastage. The Government of India's Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) aims to enhance water efficiency at the farm level through micro-irrigation [7]. Moreover, adopting water-smart agricultural practices like rainwater harvesting, crop rotation, and using drought-resistant crop varieties can further augment water conservation efforts.

Climate change poses additional challenges to water resources in agriculture. It alters precipitation patterns, leading to irregular and unpredictable rainfall, exacerbating water scarcity issues [8]. In India, climate change is expected to cause spatial and temporal variations in water availability, impacting both the quantity and quality of water resources. For instance, the Himalayan glaciers, a crucial source of India's river systems, are receding due to global warming, affecting the flow in major rivers like the Ganges and the Indus, which are lifelines for India's agriculture [9]. These changes demand adaptive strategies in agricultural water management to ensure sustainability. Integrating climate-resilient agricultural practices, such as adjusting sowing dates, water-saving irrigation techniques, and employing climate-smart agricultural technologies, is imperative to mitigate the impacts of climate change on water resources in agriculture.

3. TRADITIONAL WATER MANAGEMENT PRACTICES

The landscape of Indian agriculture has been historically rich with various traditional water management practices, reflective of the diverse climatic zones and cultural heritage of the country. These practices, deeply rooted in local knowledge and environmental conditions, have been instrumental in harnessing and conserving water for agricultural purposes for centuries. One of the most prominent traditional methods is the use of 'tankas,' rainwater harvesting structures commonly found in the arid and semi-arid regions of Rajasthan.

These tankas are small tanks, often built inside the courtyards of houses, and are used to collect and store rainwater for drinking and irrigation purposes [10]. Another notable practice is the 'Ahar-Pyne' system in Bihar, an indigenous floodwater harvesting method. Ahars are small reservoirs with embankments on three sides, while Pynes are canals that divert river water to

Table 1. Necessity of water conservation in agriculture

Necessity	Explanation
Reducing Water Scarcity	With the growing global population and climate change, water scarcity is becoming more acute. Agriculture, being a major user of water, needs efficient management to reduce wastage and ensure availability for future generations.
Enhancing Crop Yield and Quality	Efficient water use can lead to better crop yield and quality. However over-irrigation can lead to soil salinization and nutrient depletion, adversely affecting crop health.
Mitigating the Effects of Climate Change	Water conservation in agriculture helps adapt to the changing climate patterns, ensuring food security amidst unpredictable rainfall and extreme weather events.
Reducing Energy Consumption	A significant amount of energy is used in pumping and delivering water for irrigation. Water conservation methods can reduce this energy use, contributing to overall energy efficiency.
Preserving Natural Ecosystems	Over-extraction of water for agricultural purposes can harm natural ecosystems. Efficient water use helps maintain the balance in rivers, lakes, and groundwater systems.
Economic Benefits for Farmers	Implementing water conservation techniques can reduce water costs and increase profitability for farmers, especially in regions where water is a paid resource.
Ensuring Sustainability for Future Generations	Sustainable water management in agriculture ensures that future generations have access to the necessary resources for food production and a healthy ecosystem.

Table 2. Traditional water management practices in India

Practice	Region	Description	Reference
Jhalara	Rajasthan	Man-made tanks for rainwater harvesting, common in arid areas.	[15]
Baoli/Bawdi	Various	Stepwells for water storage, also social and cultural sites.	[16]
Taanka	Rajasthan, Gujarat	Underground water storage in homes for drinking water.	[17]
Ahar-Pyne	Bihar	Floodwater harvesting system with reservoirs (Ahars) and channels (Pynes).	[18]
Kuhls	Himachal Pradesh	Gravity-based water diversion channels for irrigation in mountains.	[19]
Zabo (Ruza)	Nagaland	Combines forestry, agriculture, and water conservation; channels runoff to fields.	[20]
Khadin	Rajasthan	Rainwater harvesting for agriculture using long earthen embankments.	[21]
Vav	Gujarat	Architecturally complex stepwells for water storage and social activities.	[22]
Surangam	Kerala	Horizontal tunnels in hillsides for groundwater collection.	[23]
Johads	Rajasthan, Haryana	Small earthen dams for rainwater capture and groundwater recharge.	[24]
Eri (Tank)	Tamil Nadu	Man-made lakes or reservoirs for water storage, irrigation, and sometimes fish cultivation.	[25]
Pat	North-Eastern India	Bamboo drip irrigation system in hilly areas for crops like pepper.	[26]

the fields. In the southern state of Karnataka, 'Kattas,' or temporary check dams, are constructed across streams to impound water. Similarly, in the northeastern region, particularly in states like Meghalaya, the living root bridges, an amalgamation of traditional knowledge and nature, serve as a unique method of water conservation and management [11]. Despite their sustainability and low environmental impact, traditional water management practices in India face several limitations and challenges in the context of modern demands. One of the primary challenges is the scalability and modernization of these practices to meet the needs of the increasing population. As India's population continues to grow, the pressure on water resources intensifies, making traditional practices insufficient to meet the growing demands [12]. Moreover, many of these practices require community involvement and collective management, but with the increasing individualization and privatization of water resources, community participation has dwindled. Urbanization and industrialization also pose significant threats to traditional water management systems. As cities expand, many traditional water bodies and harvesting structures are encroached upon or neglected, leading to their deterioration [13]. The transition from traditional to modern water conservation approaches in Indian agriculture has been gradual and necessitated by the need to enhance efficiency and productivity. The government of India, recognizing the limitations of traditional systems and the urgency of conserving water, has initiated several programs to promote modern water conservation techniques. The Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), launched in 2015, aims to extend the coverage of irrigation and improve water use efficiency through various interventions, including drip and sprinkler irrigation [14]. Modern methods like micro-irrigation not only conserve water but also increase crop yield and quality. The National Water Mission under the National Action Plan on Climate Change also promotes water conservation, focusing on a more integrated approach to water management .

4. MODERN WATER CONSERVATION TECHNIQUES

In the context of India, a country grappling with the dual challenges of water scarcity and the need to boost agricultural productivity, modern water conservation techniques are not just innovations but necessities. The advancements in irrigation technology have been pivotal in this regard. Drip irrigation, one of the most significant advancements, epitomizes efficient water use in agriculture. In drip irrigation, water is delivered directly to the roots of plants in a slow and steady manner, minimizing evaporation and ensuring that the plants receive water and nutrients in the most efficient way possible [27]. The adoption of drip irrigation in India has been growing, particularly in water-stressed states like Maharashtra and Gujarat, driven by both government initiatives and farmer awareness. Studies have shown that drip irrigation can save up to 60% of water compared to conventional flood irrigation while increasing crop yields. Sprinkler systems, another technological advance, have also gained popularity in India. These systems simulate rainfall and are particularly useful in uneven terrains where traditional irrigation methods are impractical. Sprinklers distribute water more evenly and can lead to significant water savings compared to surface irrigation methods [28]. The Government of India has been promoting sprinkler systems through various schemes and subsidies, recognizing their potential in enhancing water use efficiency in agriculture. Subsurface irrigation is a less common but highly efficient irrigation method where water is applied below the soil surface, directly to the root zone. This method has the advantage of reducing evaporation losses and minimizing weed growth. However, its adoption in India is limited due to higher initial costs and the need for technical expertise [29]. Beyond advancements in irrigation technology, water-efficient agricultural practices are equally crucial in conserving water. Crop rotation and diversification are traditional practices that have been revitalized in the modern context. Rotating crops and diversifying plantings can improve soil health, reduce pest and disease pressures, and lead to more efficient use of water. In India, initiatives like the National Food Security Mission have been encouraging farmers to diversify crops, especially in regions dominated by water-intensive crops like rice and wheat. Soil moisture management is another vital aspect of water-efficient agriculture. Practices such as conservation tillage, maintaining soil organic matter, and using soil moisture sensors can optimize water use and enhance crop yields [30]. The Indian Council of Agricultural Research (ICAR) has been promoting soil moisture conservation techniques through training and extension activities. Mulching and cover cropping are simple yet effective techniques for conserving soil moisture. Mulching involves covering the soil with organic or inorganic materials, which helps retain moisture, reduce evaporation, and suppress weed growth. Cover cropping, on the other hand, involves growing certain crops (cover crops) primarily for the benefit of the soil rather than for crop yield. These practices have been gaining traction in India, particularly in organic farming and sustainable agriculture circles [31].

4.1 Use of Climate-Smart Agricultural Practices

The concept of climate-smart agriculture (CSA) has gained significant traction in India as a means to address the twin challenges of climate change and food security. In a country where a large portion of the population depends on agriculture for their livelihoods, the impact of climate change on agricultural productivity is a critical concern. CSA aims to sustainably increase agricultural productivity, adapt and build resilience to climate change, and reduce greenhouse gas emissions where possible [42]. Within this framework, several practices have been emphasized, including weather forecasting and climate modeling, the development and use of resilient crop varieties, and integrated pest and nutrient management.

4.1.1 Weather forecasting and climate modeling

Weather forecasting and climate modeling are essential components of climate-smart agriculture. These tools help farmers make informed decisions about planting, irrigation, and harvesting, thereby reducing risks associated with climate variability. In India, the Indian Meteorological Department (IMD) provides weather forecasts and agricultural advisories to farmers. With advances in technology, these forecasts have become more accurate and localized, aiding farmers in planning their agricultural activities more effectively. The Government of India's Gramin Krishi Mausam Sewa (GKMS) scheme, under IMD, delivers district-level weather forecasts. Additionally, several private and academic institutions also provide weather-related information. The use of Geographic Information Systems (GIS) and Remote Sensing (RS) technologies has further enhanced the precision of weather predictions and climate modeling in India [43].

4.1.2 Resilient crop varieties

The development and use of resilient crop varieties are vital in ensuring food security in the face of climate change. In India, research institutions such as the Indian Council of Agricultural Research (ICAR) have been at the forefront of developing climate-resilient crop varieties. These varieties are designed to withstand extreme weather conditions such as drought, heat, salinity, and flooding. For instance, drought-tolerant varieties of rice and wheat, and salt-tolerant varieties of coastal crops, have been developed and are increasingly being adopted by farmers [44]. Such innovations are crucial in a country like India, where climatic variations can significantly impact crop yields and, consequently, the livelihoods of millions of farmers.

4.1.3 Integrated pest and nutrient management

Integrated pest and nutrient management is another critical aspect of CSA, focusing on optimizing the use of chemical inputs and promoting ecological practices. In India, excessive and inappropriate use of chemical fertilizers and pesticides has led to soil and water pollution, besides disrupting ecological balances. Integrated Pest Management (IPM) and Integrated Nutrient Management (INM) offer more sustainable alternatives. IPM involves the use of a combination of biological, cultural, physical, and chemical tools in a coordinated way to manage pests [45]. Similarly, INM aims to optimize the health and productivity of soil by balancing the use of organic and inorganic fertilizers. Programs like the National Project on Organic Farming (NPOF) and the Paramparagat Krishi Vikas Yojana (PKVY) have been promoting these practices across India, contributing to sustainable agriculture and environmental conservation.

Table 3. Modern water conservation techniques

Technique	Description	Reference
Rainwater Harvesting	Collecting and storing rainwater for reuse before it reaches the ground.	[32]
Drip Irrigation	Delivering water directly to the roots of plants, minimizing evaporation and runoff.	[33]
Greywater Recycling	Reusing water from sinks, showers, and washing machines for gardening and flushing toilets.	[34]
High-Efficiency Toilets	Toilets designed to use significantly less water per flush than standard toilets.	[35]
Water-Sensitive Urban Design	Integrating the urban water cycle, including stormwater, groundwater, and wastewater management into urban design.	[36]
Smart Irrigation Systems	Utilizing advanced technologies like sensors and IoT for efficient irrigation management.	[37]
Artificial Recharge of Aquifers	Techniques like percolation tanks, recharge wells, and rain gardens to replenish groundwater.	[38]
Desalination	Removing salts and minerals from saline water to produce fresh water.	[39]
Water Footprint Reduction	Strategies to reduce water use and waste in industries and agriculture.	[40]
Rooftop Gardens	Using green roofs to absorb rainwater and reduce runoff.	[41]

5. THE ROLE OF TECHNOLOGY AND INNOVATION

In the realm of Indian agriculture, technology and innovation play pivotal roles in enhancing productivity, efficiency, and sustainability. As India grapples with the challenges of a growing population, dwindling natural resources, and climate change, the adoption of advanced technologies becomes increasingly crucial. The foray into precision agriculture involving use of sensors and the Internet of Things (IoT) in water management, data-driven approaches, and the exploration of innovative solutions are transforming the Indian agricultural landscape.

5.1 Precision Agriculture

Precision agriculture in India is an emerging field that integrates advanced technology into farming practices to increase efficiency and manage resources more effectively. The application of sensors and the Internet of Things (IoT) in water management marks a significant stride in precision agriculture. Sensors deployed in fields can provide real-time data on soil moisture, temperature, and nutrient levels, enabling farmers to make informed decisions about irrigation and fertilization [46]. IoT technology facilitates the remote monitoring and control of irrigation systems, optimizing water usage and reducing wastage. Projects like the Digital India initiative have been instrumental in promoting IoT in agriculture. Remote sensing and satellite imagery have revolutionized agricultural monitoring and management in India. This technology provides detailed data on crop health, soil conditions, and water resources over large areas, which is invaluable for large-scale agricultural planning and decision-making [47]. ISRO’s satellite program has been pivotal in providing satellite data for agricultural applications, supporting crop acreage and yield estimation, drought monitoring, and soil health mapping.

5.2 Data-Driven Approaches for Water Management

The use of data-driven approaches in Indian agriculture, particularly concerning water management, has shown promising results in enhancing water use efficiency and supporting sustainable practices. Artificial Intelligence (AI) and machine learning have started to make an impact in Indian agriculture, particularly in predictive analytics and decision-making processes. AI algorithms can analyze data from various sources to predict weather patterns, pest infestations, and crop diseases, enabling farmers to take preventive measures [48]. Machine learning models can also optimize irrigation schedules based on weather forecasts and soil moisture levels, significantly conserving water resources. Decision Support Systems (DSS) are computer-based tools that use data and analytical models to aid farmers in decision-making. In India, DSS integrates data from remote sensing, weather forecasts, and on-ground sensors to provide farmers with actionable insights regarding planting, irrigation, and harvesting. These systems have become increasingly important in managing the complexities of farm management in the context of climate change and resource limitations.

5.3 Innovative Solutions and Future Prospects

The exploration of innovative solutions and their future prospects in Indian agriculture is critical for the sustainable management of resources and adaptation to changing environmental conditions. Hydrogel technology, which involves the use of super-absorbent polymers to improve soil water retention, is an emerging field in India. These hydrogels can absorb and retain large amounts of water, releasing it slowly to the plants as needed [49]. This technology is particularly beneficial in arid and semi-arid regions, where water scarcity is a significant challenge. Solar-powered irrigation systems are gaining popularity in India as a sustainable and cost-effective solution for irrigation. These systems use solar panels to power water pumps, eliminating the reliance on diesel or electric pumps. The government’s initiatives, like the KUSUM scheme, aim to promote solar energy in agriculture, reducing the sector’s carbon footprint and enhancing farmers’ incomes.

6. POLICY, EDUCATION, AND COMMUNITY INVOLVEMENT

In the realm of advancing water conservation in Indian agriculture, the triad of policy, education, and community involvement plays a crucial role. Effective water management and conservation in agriculture require not just technological solutions but also robust policy frameworks, Civil Society, community engagement including gender, and educational initiatives. These elements work synergistically to create an environment conducive to sustainable water use and management.

6.1 The Importance of Supportive Policy Frameworks

Supportive policy frameworks are fundamental in shaping and guiding water conservation efforts in agriculture. These frameworks encompass both government initiatives and international cooperation. The Government of India has implemented various initiatives and regulations to promote water conservation in agriculture. Policies such as the National Water Policy, Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), and the Atal Bhujal Yojana focus on enhancing water use efficiency, promoting micro-irrigation, and replenishing groundwater levels. These initiatives aim to address the challenges of water scarcity, inefficient water use, and the degradation of water resources. International cooperation and aid play a significant role in bolstering India's water conservation efforts in agriculture. Collaborations with organizations such as the World Bank, the International Water Management Institute (IWMI), and the Food and Agriculture Organization (FAO) have facilitated the exchange of knowledge, technology, and resources. These partnerships have supported various projects and research initiatives aimed at improving water management practices in India [50].

6.2 Community-Based Water Management Strategies

Involving local communities is vital for the success and sustainability of water management strategies. Community-based approaches ensure that the solutions are locally relevant and widely accepted. Farmer cooperatives and water user associations are instrumental in promoting participatory water management. These organizations empower farmers to collectively manage water resources, make decisions regarding water allocation, and implement water-saving techniques [51]. The formation of these groups has been encouraged under various government schemes, fostering a sense of ownership and responsibility towards water resources among the farming community. NGOs and local organizations play a pivotal role in grassroots-level water conservation initiatives and mindset change. Organizations such as the Foundation for Ecological Security (FES) and the Watershed Organisation Trust (WOTR) work directly with rural communities, facilitating the implementation of water conservation projects, capacity building, and knowledge dissemination.

6.3 Education and Awareness

Education and awareness are key components in fostering a culture of water conservation and sustainable agricultural practices. Training programs for farmers are essential in equipping them with the knowledge and skills required for effective water management. These programs, often conducted by government agencies, research institutions, and NGOs, cover a range of topics including efficient irrigation techniques, soil health management, and climate-smart agriculture. Public awareness campaigns and educational outreach activities through Farmer Field Schools help in creating broader awareness about the importance of water conservation. Initiatives such as the 'Jal Shakti Abhiyan' and the 'Catch the Rain' campaign by the Government of India aim to engage citizens in water conservation efforts, highlighting the role of each individual in safeguarding water resources [52].

7. CASE STUDIES AND SUCCESS STORIES

In the landscape of Indian agriculture, numerous regional case studies and success stories showcase the effective implementation of water conservation practices. These examples not only highlight the potential of such practices in enhancing sustainability and productivity but also offer valuable lessons and models that can be replicated in other regions facing similar challenges.

7.1 Regional Case Studies Showcasing Effective Water Conservation Practices

India, with its vast and diverse agricultural zones, presents a rich tapestry of successful water conservation initiatives. One notable example is the state of Gujarat, which has implemented the Sardar Patel Participatory Water Conservation Scheme. This initiative encouraged the construction of check dams and farm ponds, leading to significant improvements in groundwater levels and agricultural productivity. Another exemplary case is the Hiware Bazar village in Maharashtra, which transformed itself from a drought-prone village to a prosperous community through community-led watershed management and water conservation practices [53].

7.2 Analysis of the Impact of These Practices on Sustainability and Productivity

The impact of these water conservation practices on sustainability and agricultural productivity is profound. In Gujarat, the construction of check dams and farm ponds under the state's water conservation scheme not only improved groundwater levels but also increased the area under cultivation and crop yields, enhancing the livelihoods of farmers [54]. Similarly, the success of Hiware Bazar is attributed to the holistic approach towards water conservation and management, which included measures like rainwater harvesting, recharging wells, and changing cropping patterns. This led to a remarkable increase in water availability, agricultural output, and a reduction in migration due to droughts

8. CHALLENGES AND BARRIERS TO IMPLEMENTATION

Implementing water conservation techniques in Indian agriculture is fraught with various challenges and barriers, ranging from economic and financial constraints to technological, social, cultural, and environmental hurdles. Each of these aspects plays a critical role in shaping the effectiveness of water conservation initiatives.

8.1 Economic and Financial Constraints

One of the primary challenges in implementing water conservation practices in India is the economic and financial constraints faced by farmers. Many water conservation technologies, such as advanced irrigation systems, require significant investment, which can be a deterrent for small and marginal farmers who constitute a large portion of the Indian farming community. The high initial costs of setting up systems like drip irrigation or purchasing water-efficient machinery are often beyond the reach of these farmers. Although government subsidies and schemes are in place to offset some of these costs, issues like delayed payments, bureaucratic hurdles, and lack of awareness often limit their effectiveness [55]. Furthermore, the uncertainty of returns on investment due to factors like market volatility and climatic risks adds to the financial burden on farmers.

8.2 Technological and Infrastructural Limitations

Technological and infrastructural limitations are significant barriers to the adoption of modern water conservation practices in Indian agriculture. Many regions in India lack the basic infrastructure required for efficient water management, such as well-maintained canals, water storage facilities, and proper irrigation networks [56]. In addition, there is often a gap between the available technology and the skills or knowledge of the farmers. The lack of training and technical support for operating advanced irrigation systems or utilizing data-driven agricultural tools hinders their widespread adoption. This scenario is compounded by issues like erratic electricity supply and inadequate maintenance services for agricultural machinery.

8.3 Social and Cultural Barriers

Social and cultural barriers also play a crucial role in the implementation of water conservation techniques. Traditional farming practices are deeply rooted in many rural communities, and any change is often met with resistance. There is a general reluctance to adopt new methods without seeing tangible and immediate benefits. In addition, social structures and power dynamics within communities can influence decision-making in agriculture, often limiting the participation of marginalized groups such as smallholder farmers, women, and lower socioeconomic classes in water management decisions [57]. These dynamics can hinder the collective action needed for effective water conservation.

8.4 Environmental Concerns and Trade-offs

Finally, environmental concerns and trade-offs are crucial considerations in the implementation of water conservation practices. While the primary aim of these practices is environmental sustainability, they can sometimes have unintended ecological impacts. For instance, the shift from flood irrigation to micro-irrigation systems can lead to the reduction of water logging and salinity but may also reduce groundwater recharge in some areas [58]. Similarly, the use of plastic materials in drip irrigation poses challenges in terms of disposal and environmental pollution. Balancing the immediate needs of water conservation with long-term ecological sustainability remains a complex and ongoing challenge.

9. CONCLUSION

Advancing water conservation in Indian agriculture is crucial for sustainable resource management and the future of food security. This comprehensive review has highlighted the multifaceted approaches ranging from traditional water management practices to innovative, technology-driven solutions. While significant strides have been made through government initiatives, technological advancements, and community participation, challenges such as economic constraints, technological gaps, social and cultural resistance, and environmental concerns persist. Addressing these challenges requires integrated efforts involving policy support, technological innovation, community engagement, and education. As India continues to navigate these complexities, the lessons learned, and the successes achieved offer valuable insights not only for the nation but also for other countries grappling with similar water resource challenges in the agricultural sector.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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