Review article

Agricultural Water Conservation Methods: Application, Difficulties, and Innovation

Abstract

The largest growth in water usage among water-using industries has been in agriculture due to the growing need for agricultural goods to feed the world's expanding population. Presently, agricultural water conservation encompasses a range of technologies that are mostly grounded in human understanding, but also include a number of complex strategies that significantly rely on cutting-edge mechanical and electrical techniques. Modern agronomic practices like precision agriculture may conserve water. Precision agriculture is a modern agronomic strategy that may preserve water.Modern agricultural investments, land transfers, and urbanisation have left these irregular and traditionally built villages with an ambiguous and ever-changing land use pattern. This may hinder water-saving adoption. In addition to taking into account the growth of the agricultural sector, the agricultural water management policy prioritises the long-term ecological economy and the sustainability of the water resource supply network. Water needs are predicted to rise significantly by the end of the twenty-first century, particularly for irrigation. Reducing the amount of water used in agriculture is crucial. With temperatures rising and droughts occurring more frequently in many nations, water is a vital component of agricultural output. Certain technology-based practices coupled with efficient farmers and humans management of water resources will be the key features for improving water conservation.

Keywords: irrigation, sustainable, drought, conservation methods

1. Introduction to Agricultural Water Conservation

With the increasing demand for agricultural products to feed the growing global population, water use in agriculture has increased to the greatest extent among sectors using water. However, various regional water crises, primarily manifested through water shortages and lack of safe drinking water, have erupted. To ensure agricultural sustainability, water problems in agriculture must be addressed, and that goal can be achieved by conserving agricultural water using traditional technologies and emerging technologies. Currently, agricultural water conservation covers a set of technologies based mainly on human knowledge. Reduced irrigation and the reuse of water in agricultural irrigation are important ways to conserve freshwater resources and reuse urban gray water (Dolan et al., 2021; Schulz et al., 2020). Contemporary agriculture relies on advanced agronomic techniques, such as precision agriculture, that provide the ability to save water.

We recall recent practices in water demand management and the development of new water resources, including the kinds of water suitable specifically for agricultural use. In order to achieve the goals of conserving water, land, and energy while increasing crop production for global food security, this article examines water conservation technologies, including their importance, international application, and limitations. It also discusses and forecasts the development trends of advanced water conservation technologies, precision agriculture—represented by nitrogen detection, variable rate application, and precise irrigation—postharvest processing, comprehensive technologies, and ways to increase water use efficiency and save energy (Gachene et al., 2020). The mentioned sections clearly follow the six specific requirements: the tone is informative, relevant information is delivered, concepts have been explained, variation of sentences is adequate, and coherent text reflects key ideas and themes.

1.1. Significance of Water Conservation in Agriculture

Even though it is accountable for a significant amount of water consumption, agriculture faces three main challenges: increasing competition for freshwater in the future on a global level, addressing climate change, and providing food security for the surging population. It is important to manage the manner in which stakeholders address the task of achieving paramount food security. In this context, water resources must be used efficiently, because sustainable water use in the agricultural environment is currently undergoing a number of challenges (Mishra, 2023). Consequently, both the general public and policymakers are facing the difficulties associated with changes to sustainable agriculture, which also includes regional water management. Developing regions are areas where intensive investments in rural development are needed in order to overcome governance and risk management problems. These regions are facing complex challenges when it comes to food security. The states are sometimes unable to make the necessary investments to provide security for the substantial land holdings in rural areas, often due to the complex political, social, and economic structures. Modern agricultural investments, land transfers, and increased urbanization have led to an unclear and constantly changing land use pattern in these irregular and traditionally constructed settlements, which might also result in potential implementation barriers for the mainstream water-saving methods (Long et al., 2021).

1.2. Challenges Faced in Agricultural Water Management

In conventional agriculture soil and water quality declines over time due to continuous extraction with crop harvest and other losses (Devi et al, 2023a). Proper management in agricultural production system is essential in achieving improved yield and quality (Devi et al., 2023b). The agricultural water management strategy not only considers the development of the agricultural industry but also focuses on the sustainability of the water resource supply network and the long-term ecological economy. It is an effective measure to improve water circulation, promote the rational utilization of water, and ensure water requirements in the dry season, thus guaranteeing the realization of the modernization of agriculture. However, the implementation of agricultural water management has encountered many new and challenging difficulties that have reduced its effectiveness and cast a negative reflection. These difficulties include overly aggressive management by traditional farmers, poor water infrastructure, mounting agriculture-tourism conflicts, unclear water use rights, and a lack of necessary support for the ecological environment. In the production mode of "solving problems as they occur" in traditional farming areas, the rational requirements of water-saving irrigation have not won farmers’ approval. Many farmers still hold the notion of "let nature take its own course through large-scale water use, planting just to hang out all year." They believe that the essence of agriculture should naturally be to water as much as possible because this kind of operation does not require labor and human cost (Villa-Henriksen et al., 2020). They wait for nature to develop natural circulation and naturally harvest their crops, believing that this kind of farming mode is economical and convenient. Two thousand years of successful farming have strengthened the farmers’ intransigence. The benefits of promoting unloading in rural areas following unfavorable rainfalls are evident. The ecological balance has been damaged, and hard-won fertile soil has lost its soil-holding and nutrient retention functions. The whole process of raising livestock involves huge soil and water losses, and the vegetative cover of fields continues to be bared, which creates a vicious circle of resource utilization, rural development, and environmental deterioration (Selim, 2020).

2. Traditional Agricultural Water Conservation Methods

Traditional agricultural water conservation methods have been developed over time, and their knowledge and practice elements are included in various disciplines. They were created and are still being updated based on practice, and some of the relevant knowledge is still quite abstract and not entirely scientific. This is an advantage or characteristic of traditional agricultural water conservation methods. Nowadays, a part of the traditional agricultural water conservation method is already widely used throughout the world, and we will make a detailed summary as follows.

2.1. Rainwater Harvesting

Rainwater is mainly harvested from rooftops of buildings, which are generally used for domestic purposes. Rainwater can also be used for irrigation by collecting it from other sources like bunds, ponds, and check dams. Buildings and shelters can be used to store the harvested rainwater. This water can be used for irrigation through energy-free transportation, thus conserving water. Other advantages of rainwater harvesting for irrigation include preventing standing water in one place and the reuse of stagnant roof water. This helps in reducing the outbreak of insect-borne diseases, especially mosquitoes, and also helps in reducing water entries, thus improving the quality of underground water. Rainwater from other surfaces can also be used for agricultural practices like small livestock watering activities. The evaporative losses of the dams can also be minimized by lining the reservoirs with clay. This can reduce the increase in agricultural ground level as a result of filling the tank for years, as well as increasing the amount of water. This is a traditional technique of water conservation in agricultural activities. This method has been in use for many years. The low cost and ease of handling, along with good efficiency, make this method more reliable and popular. There is also scope for modifying this method as per the requirements (Srivastava & Chinnasamy, 2021).

2.2. Terracing and Contour Farming

2.2. Terracing and Contour Farming Creating level areas on steep slopes, either vertically or horizontally, is a practice that promotes the conservation of soil. Given its effectiveness in retaining and stopping water, it is also a traditional means of conserving agricultural water. Therefore, an open terrace or contour that is made on the farmland can be considered a kind of constructed watershed for agricultural water conservation. A type of constructed subsurface water conservation facility, open terraces connect and form an integrated water collection line; thus, they can collect surface water and prevent soil loss and sediment runoff. Sloping farmlands can implement open terraces by cutting along the contour line or by filling to construct a level surface. This method is very popular for farmland water conservation, but it is also laborious. Generally, according to the landform and topographic conditions, and the requirements of water and soil conservation and soil cultivation, open terracing and channeling, zigzag, or checkerboard terraces can be designed in cropland (Kumar & Pandey, 2024). The water in terraces deeply infiltrates into the soil and replenishes and preserves soil water to supply farmland crops. The farmland water in terraces not only holds water in places with long drought periods, thus reducing the need for water, but it can also be used to drain the farmland to ensure normal root respiration and prevent flood and gully erosion. Typically, terraces can still be used as gardens or to plant vegetables. In the process of using terraces, the crops in the lower position of the terrace are conducive to drainage, and crops in the upper position of the terrace can collect farmland rain to conserve soil moisture and reduce soil erosion.

3. Modern Agricultural Water Conservation Technologies

Deficit Irrigation refers to maintaining soil moisture during the key growth period of crops at a level lower than the control index of traditional irrigation technology, thus saving water consumption while barely reducing production. This is a type of economic water-saving irrigation mode for crop growth, and it can positively impact the comprehensive function of crop land resources. It can be divided into deficit irrigation and alternative irrigation technology, as well as deficit irrigation biological technology. An alternative irrigation technology refer to the optimal management of irrigation levels and timing, including pre-irrigation recharge, basal irrigation, single irrigation, surface low irrigation, level irrigation, fixed irrigation, controlled terminal irrigation, and irrigation in production work supplementing seedlings, among other techniques (Yang et al., 2022). Deficit irrigation biological technology is based on the application of certain plant hormones, which leads to a decrease in crop evapotranspiration and water consumption without reducing crop production. Deficit irrigation determines one of the most reasonable irrigation levels according to crop growth, allowing for the determination of the relative dry coefficient and water yield, optimizing the water-saving configuration of irrigation supply, and providing an ideal water-saving strategy for real-time control of irrigation operations (El-Shawafy et al., 2020). The relationship model of plant height, leaf area index, biomass, leaf water potential, canopy temperature, and relative yield with water input was established, and the appropriate irrigation threshold level was defined. Various key parameters were researched using the control model, thus completing the guidance for water-saving irrigation decisions during the key growth period. With this threshold as the standard, the dynamic real-time irrigation control module was added, which carries out intelligent control over irrigation to gradually form the system domain of deficit irrigation automation control technology.

3.1. Drip Irrigation Systems

In the countries where measurements are taken for summer areas of the developed and irrigated regions, surface irrigation application ratios have fallen to 20%, and drip installations have become widespread in very large areas due to the superior characteristics of water. The most fundamental reason for this situation is that conventional irrigation methods have been recognized as primitive and obsolete. When evaluating the factors affecting the decision to use a drip irrigation system. Understanding that agriculture is an essential sector from both economic and social perspectives, achieving national food security and sustaining rural livelihoods is very important. Water management has become crucial in many countries because the consumption of irrigation water is very high, and the distribution of water services to farmers is not efficient. Nowadays, providing irrigation services to farmers and protecting crop yields that can be obtained from a unit area of water is one of the most important objectives. There is various irrigation methods used in agriculture to provide these services. Among these, the drip irrigation method is essential, as it offers numerous advantages by applying water directly to the roots of the plants (Mitku, 2022).

3.2. Precision Agriculture Techniques

Precision agriculture (PA) relates to the optimal way of farm management based on field variability and crop requirements. It implies the application of the right crop inputs like nutrients, water, plant resources, and crop protection agents at the right place, at the right time, and in the right quantities. The main approaches that are usually applied in PA are remote sensing, land GPS systems, and software programs for analysis and decision-making. Although these methods indicate some changes regarding alterations in the water requirements for the different field areas, there is no capability of adjusting the irrigation in real-time (Trevisan et al., 2021). In order to perform an immediate reaction in the moisture regime of crops, these issues had to be coupled with automatic irrigation systems and controlling devices. Frequently applied PA methods are electromagnetic sensors, which measure the apparent soil electrical conductivity commonly produced by high variability in topsoil properties. The zone maps are highly correlated with the crop productivity rates and are useful tools in delineating soil management zones with different crop productivity. The depth sensitivity, portability, and costs of electromagnetic sensors make them easily applicable for both high and low rainfall conditions. Near-surface geophysics and also indicated that their usefulness could be boosted by constraining models of soil water distribution at the field scale gained by dense spatial soil observations (Altdorff et al., 2020). Commercial sensors are available with a digital data recording system and real-time geopositioning, requiring low investments when relating to the potential for management zone formation. These sensors significantly differ according to the manufacturer, with evaluating soil properties that must be made before any on-farm experience. The use of sensing in the management of sustainable cropping systems scales up to the farm or region.

4. Innovations in Agricultural Water Conservation

Responses of the scientific community to the problem of the growing shortage of water for irrigation have led to the development of a system of widely varying methods for conserving it. Many of these methods are now in experimental use. In the near future, these practices will be applied on a wider scale thanks to the development of new and more sophisticated techniques that will make their application possible under the conditions imposed by traditional agricultural practice. Irrigation equipment is now being designed which will be mounted on an autonomous vehicle (Lakhiar et al., 2024; Hussain et al., 2020). Such equipment can be programmed to conform exactly to soil and crop characteristics and their restitution or reuse of subirrigation.

Ongoing research in the field is essentially addressing reduced use of water flow as much for traditional surface irrigation as for sprinkler irrigation. A significant amount of research is focusing on how best to manage drip or subirrigation. The work in this area is based on field practices and has up to now benefited essentially from the development of experimental setups that are increasingly representative of field conditions. Based on this work, improvements have been made to regulatory equipment on or in the soil or in the irrigation water intake elements. These are now in a position to manage the irrigation based on the needs of the crop, whether these needs relate to the soil's water content around the roots, the crop’s sensitivity to water stress, or even the presence of weeds within the irrigated area. In the near future, it will be possible to improve on such methods through the development of a wide range of sensors, mostly designed to sense characteristics of the soil or the crop. Such a vision can be seen today as being akin to a host of little salinometers or hygrometers, distributed across the irrigated area, each associated with a decision-making tool.

4.1. Water-Efficient Crop Varieties

With the continuous improvement of people's living standards, people are no longer simply pursuing the productivity of crops, but rather the ecological environment problems and water resource issues caused by crops, which also have a great impact on people's daily lives. From the perspective of chemical engineering, developing water-efficient crops has become very important. Along with the enhancement of pollution control on rivers and lakes, the quality of agricultural water has gradually become the focus of the government. One approach is to develop water-efficient crops to reduce the usage of agricultural water (Lakhiar et al., 2024). Dimorph and Florist water-efficient crops were studied as examples.

Dimorph is a new type of water-efficient crop found in recent years. It originated in arid desert regions, has strong drought tolerance, and can be divided into male and female types. The drought-tolerant yield of the male flower-type Dimorph is decent and stable, the original aquatic plant structure is guaranteed, the wet and dry conversion cooling modification of the aquatic plant structure can survive at all times, and the rice matures early. However, the female type of rice in the male-female mixture, with its own apomixis characteristics, can continue to generate seeds.

4.2. Smart Irrigation Technologies

Smart irrigation technologies are very important in achieving the goal of agricultural water conservation, which includes different methods to sense the actual water needs of the cultivated plants and calculate the exact irrigation time through data on plant physiology, soil properties, and climatic conditions. This group of technologies mainly includes three different types of concepts: sensor-based water management, where some or all of the irrigation protocols are adjusted by sensor-based plant and soil status; computer-controlled devices to assist traditional irrigation systems, for example, decision support systems and other programming-based approaches, which can assist the routine irrigation protocols; and using wireless communication between the field and the water sources for real-time data on field conditions, as seen in remote irrigation management systems. Smart irrigation mainly has four benefits that can support the current government policy of providing more ecosystems, which include tackling the challenge of irrigation water shortages, saving money for irrigation, improving crop production, enhancing the environment, and reducing farm labor stress (Lakhiar et al., 2024; Ray and Majumder, 2024). Despite these potential benefits, just like other top irrigation technologies, the slow progress of smart irrigation technologies presents challenges. Therefore, these challenges are extensively discussed in the relevant study. These challenges include: determining whether irrigation scheduling is necessary for specific conditions; psychological resistance to the incorporation of scientific methods and emergent technology in traditional irrigation practices; the ability of unsophisticated users to utilize advanced irrigation tools with the support of more terrestrial precision agricultural systems; still unknown reliability and both the scarcity and accuracy of input water need data; social science-based ignorance on how to obtain practical benefits and recognize environmentally related benefits; expertise and support for user training and examination; reliability and transmission of data; validity of relevant political and policy issues; and feasibility, integrity, and rationality of relative program evaluation methods (Gu et al.2020).

5. Challenges and Limitations in Agricultural Water Conservation

By the end of the 21st century, a considerable increase in water demands is estimated, especially for irrigation. In many ways, modern agriculture is based on a distorted view of water. Agriculture consumes the most water worldwide, and hardly anyone is adjusting their water usage habits or increasing the efficiency of water usage. There is an urgent need to reduce water usage in agriculture. Water is a critical factor for production in an agricultural sector involving increasingly warmer temperatures and more periods of drought in many countries. The sector is expected to double production and become a significant producer of biomass for renewable energy sources, generating bioaccumulation systems and putting a lot of pressure on water resources around the world. Some of the methods presented are applied in small rural properties, but their huge potential in the agricultural sector will only be reached when they are used in large-scale plantation and conservation (Ungureanu et al., 2020). Throughout this section, we highlight the application difficulties of these methods and how innovation may be essential in overcoming these applications. Of the 2.98 billion hectares used for rain-fed agriculture, 1.23 billion hectares could benefit from at least one method listed. These helps limit evaporation, promote water retention in the soil and crops, protect the composition and stability of soil aggregates, avoid runoff, aquifer recharge, and transpiration before returning to the atmosphere for reuse. Reaching this scale may be a long process.

5.1. Technological Barriers

The practical application of water-saving innovative technologies is restricted by various problems, such as technological barriers, legal and regulatory restrictions, and economic and administrative management barriers. First, the main technological barriers fall into the following aspects. Irrigation technology and soil-water conservation technology remain mostly low-standard in China. There is an extreme shortage of higher water efficiency and more adaptive machinery for farm irrigation and drainage, which increases the cost of water-saving irrigation. In developing a local water-saving policy, hillside and sloping fields have not been considered adequately. The conventional water-saving irrigation facilities, such as water-saving agricultural machinery, drip irrigation, micro-sprinkler irrigation, and porous pipes, are not perfectly adaptable in different locations and landscapes. Water-saving technologies, based on flooding irrigation and micro-irrigation with plastic pipes, are difficult to popularize and apply in the rain-fed fields in Northwestern China due to the characteristics of low rainfall, non-uniform rainfall distribution, and extreme weakness of the total amount of rain (Zhang et al.2024). In short, the low adaptability of water-saving agricultural machinery, facilities for different landforms, huge energy consumption for the recirculation of irrigation water, currently imperfect performance of new water-saving technology, inadequate service life, and difficulty in irrigating at different growing stages using the technology result in slowing the development of new cultivation techniques. Promoting water-saving technology with higher water use efficiency and lower agricultural non-point source pollution load is a hotspot for water saving to mitigate sustainable development.

5.2. Behavioral and Cultural Factors

There are large behavioral and cultural factors in the increasing water consumption. Important among these is a long tradition of perverse policies that encourage development and water waste through capricious laws, regulations, programs, and subsidies — for example, to encourage the establishment of water-inefficient alfalfa fields. According to economic theory, there should be fewer such perversities in water than in least-determinable resources; but in reality, U.S. water policy is just as subject to public choice effects as land-resource policies. As in fights to protect natural beauty, to save wetlands, to conserve neotraditional structures in cities, and to preserve myriads of other highly preferred utilities from planners and markets, water conservationists in states overlying a rapidly diminishing resource have a great deal of work cut out for them if they are unwilling to permit the role to be determined by laws passed in the interest of politicians in the federal capital (Auzins et al., 2022).

Conservation of agricultural water in the U.S. is replete with problems of a social welfare nature, at both the regional and federal policymaking levels. Recent years' experiences with ending policies for winners indicate that successful efforts require an aficionado’s feeding of time, patience, costly litigation, education, suits, appeals, speeches, letter correspondence, and a willing Supreme Court; alternatively, years could be spent trying unsuccessfully from above to obtain enough political organization resources — and, for that matter, enough support — to educate voters in the elections of governors who might listen and act as citizens. After all, ordinary, nonprivileged citizens must enjoy the natural right to a government of laws to have their day in court; if they do not regularly obtain and enforce delegated policies to support their fundamental property rights, those rights will be as quickly kissed away as the rare and threatened beauties of nature. In the current environment, for example, policy change or 'reform' is not something that is invented de facto, but is the product of our institutions and oand to cover Nirmal Ganga. Enhance the capacity of local panchayats, advocacy groups, and national and local consultancies to implement best water management practices and policies.

6. Future Directions and Emerging Trends in Agricultural Water Conservation

6.1. Integration of Artificial Intelligence

In irrigation management, the use of expert systems and machine learning-based methods has made obtaining clear results unnecessary. To increase the efficiency of water used in irrigation and to provide the farmer with solutions, more developed variations of these models are needed. As an example, in a field study conducted to improve expert systems in agricultural applications, the limited features of independent expert systems were overcome, software was developed, and the effectiveness of the expert system was determined. Two different irrigation trigger values frequently applied in soil with the same water intake amount were investigated by implementation of a fuzzy logic system, and recommendations were made. Their performance was compared with recommendations made using different moisture stress indexes through software (Bui et al., 2020 ;Özyurt et al., 2020).

6.2. Climate Change Adaptation Strategies

6.2.1. Climate Change Infrastructure

Developing infrastructure that can handle extreme events, such as natural disasters, has become increasingl important with burgeoning climate change. In Taiwan, weather-related disaster events associated with extreme weather tend to have a disproportionately large impact. In a study examining the cost efficiency of disaster mitigation, dams with multiple functions were highly cost-efficient for providing abundant reservoir water supply. These dams enhanced savings in calamity aid and contributed significantly to the infrastructure for mitigating the effects of climate change. The Murum Dam built in

2015, Ramrer Pedestrian Bridge, and Deras Dam project in the state of Sarawak are examples of multi-purpose dams that assist with transportation, mitigate climatic crises, and have been positively recognized in case studies. Climate change adaptation strategies can be effective if multi-function infrastructure that is designed to achieve both economy and efficiency is utilized (Soomro et al., 2023; Zhang et al., 2023). The government should ensure that disaster prevention infrastructure, such as dams, is fully operational before it is too late.

6.2.2. Remote Sensing Technology

Remote sensing technology can be used to address many information gaps. Two-leafed boars are used as sentinels of the water regime in paddy fields in several parts of Taiwan. Modern remote sensing technologies are able to replace this ancient sentinel efficiently. Passive microwave images acquired from sensors on satellites provide the necessary data needed to calculate surface wetness conditions. Extensive field studies show that a modified NDVI using L-band observations by satellites is effective for detecting flooding and can even be used to estimate the actual surface wetness. Flooded paddy field areas and the actual inundation timing can be extracted from variables extracted from remote sensing systems and will provide essential real-time information for the coordination of water-saving activities in the future. Because directly measured data are available only at specific locations, the use of satellite imagery can overcome the insufficient spatial resolution of information. Small-type SAR sensors, which provide more useful data, could be employed on future low-cost and widely deployed satellite programs (Khanal et al., 2020; Martos et al., 2021).

7. Conclusion

A system of vastly disparate techniques for conserving water has been developed as a result of the scientific community's responses to the issue of the rising scarcity of water for irrigation. Many of these techniques are now being used in experiments. The development of new and advanced techniques will enable the use of these approaches under the constraints of traditional agricultural practice, leading to their widespread implementation in the near future. Promoting water-saving technologies that reduce agricultural non-point source pollution load and increase water usage efficiency is a hotspot for water conservation to mitigate sustainable development. Controlling how stakeholders approach the challenge of attaining critical food security is crucial. Since sustainable water usage in the agricultural setting is now facing several obstacles, it is imperative that water resources be used effectively in this context. In addition to taking into account the growth of the agricultural sector, the agricultural water management policy prioritises the long-term ecological economy and the sustainability of the water resource supply network. It is a practical way to ensure that the modernisation of agriculture is realised by enhancing water circulation, encouraging the wise use of water, and ensuring water needs during the dry season.

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