Review Article

Sustainable Water Solutions for Agriculture in Pakistan: An Overview

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Abstract | Pakistan's water resources primarily depend on the Indus River system, making it highly vulnerable to fluctuations in river flows and climatic changes. This unsustainable water usage in agriculture not only exacerbates the water crisis but also hampers agricultural productivity and food security. Agriculture accounts for 24% of the GDP while more than 90% of water consumed in Pakistan is utilized for agriculture. Pakistani has one of the best canal systems in the world and irrigation is the most water-consuming division of the country. More than 80% of the agricultural water is partitioned into wheat, cotton, maize, sugarcane, and rice. Seepage from rivers/canals, mismanagement, unequal distribution, pollution, and salinization are major contributing factors to the water crisis. Climatic conditions, global warming, and lack of rainfall are worsening agricultural losses in this arid environment. More awareness is needed in the farming community to focus on water-saving strategies, water budgeting, and using monitoring software to evaluate areas to conserve water. Government policies to equally distribute irrigation water would solve and save the country from this impending crisis. There is a need to improve storage capacity by building dams, reservoirs, and water retention ponds to help capture all available water that falls on the land. The country requires hydrogeological surveys, applied water management research for identification, evaluation, pilot testing, and demonstration of water management interventions, and practical training of stakeholders for successful pilot testing of new technologies, and sustainable practices. There is an urgent need to educate the public and develop infrastructure for better water management because of the increasing water insecurity in agriculture, low water productivity, and emerging climate issues.

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1. Introduction

Pakistan's water resources primarily depend on the Indus River system, making it highly vulnerable to fluctuations in river flows and climatic changes. Rapid population growth, inefficient water management practices, and inadequate infrastructure have resulted in an uneven distribution of water resources across different regions of the country (Nabi *et al*., 2019). In 1947, Pakistan was a water-abundant country, having more than 1600 cubic meters of water per capita. Pakistan will soon be among the most water-scarce countries, with less than 1000 m^3 of water per capita. The country depends on a single source, the Indus system, and its tributaries, fed mostly by snow and glacier melt in the greater Himalayas. According to International Monitory Fund (IMF), Pakistan is the third most vulnerable country regarding water crisis as per capita water availability is 1017 cubic meters near to scarcity threshold level of 1000 cubic meters (IMF, 2015). Pakistan is ranked first regarding water usage concerning GDP. Water is the basic input for agriculture. Emerging challenges to irrigating agricultural land are raising inadequate water availability for crop production, poor irrigation efficiency, and over/ under irrigation, leading to low water productivity (Cooper, 2018). By 2025, Pakistan is going to face an acute water crisis (FAO, 2021).

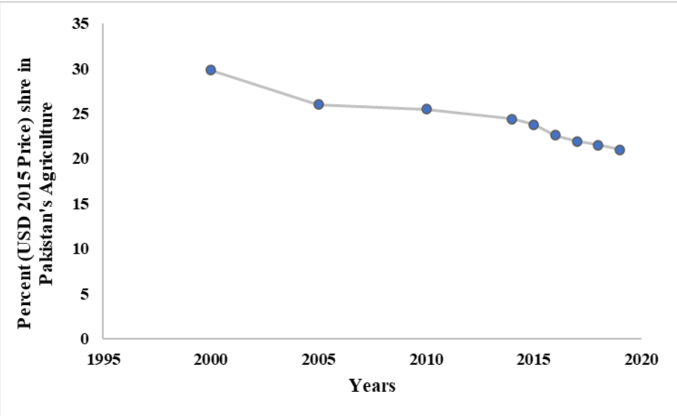

Figure 1: Year-wise percent share (USD 2015 Price) of Agriculture, Forestry, and Fishing in the GDP of Pakistan (FAO, 2021).

The National Water Policy of 2018, Punjab has a total of 90 MAF including 50 MAF of surface water, 33 MAF of groundwater, and 7 MAF of rainfall. However, the total loses are 37 MAF including 12 MAF losses from canals, 10 MAF from water courses, and 15 MAF from the field. So, the net available water is 53 MAF while the crop water requirement is 65 MAF for 43 million acres of cropped area (GoP, 2018a). So, the country's agriculture is under threat, contributing to about 24% of GDP (Pakistan Bureau of Statistics, 2022) and providing a 42.3% source of income for livelihood (GoP, 2016). However, Pakistan's share of agriculture is declining year after year (Figure 1). Pakistan is among the top 15 countries utilizing (94% of) water for agriculture (FAO, 2021), with more than 80% of it just utilized by wheat, cotton, maize, sugarcane, and rice. These crops contribute 4.32% to the GDP (GoP, 2022). Pakistan has major crops which need water in abundance. According to Food and Agriculture Organization (2011), Pakistan has an average of 494 mm of rainfall annually. Pakistan is also among the top 15 water-stressed countries (FAO, 2011). However, the ¾ area of the country has less than 250 mm of annual rainfall. 70% of our rain is during monsoon (July-August). Rivers are the major source of water followed by rainfall (Basharat, 2019). In most cases, heavy rains cause flood conditions, but there is no proper management to utilize in the future (Sheikh *et al*., 2021).

According to Water Apportionment Accord 1991 distributed 37% of surface water to Punjab, 37% to Sindh, 12% to Baluchistan, and 14% to NWFP (Anwar and Bhatti, 2018) (Figure 2). Underground water provides 33 MAF, while rainfall contributes approximately 7 MAF annually. A significant amount of water (12 MAF) loss occurs from a canal to a field water outlet. Research on water management technologies is the need of the hour for proper irrigation plans (Cooper, 2018).

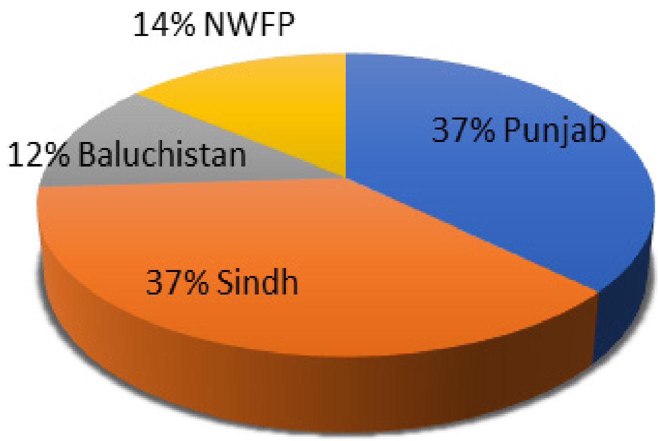

Figure 2: Distribution of water among provinces according to Indus River System Authority (IRSA) Government of Pakistan, Islamabad.

Pakistan is ranked second among countries for underground water depletion. Groundwater potential is 3000 MAF and 50 MAF is extracted annually. The country's underground water level is going down day by day and farmers could be charged per unit use of water for irrigation as the supply of this precious natural resource decreases further (ADB, 2004). Similarly, the actual surface water of the country is declining rapidly (GoP, 2022) (Figure 3).

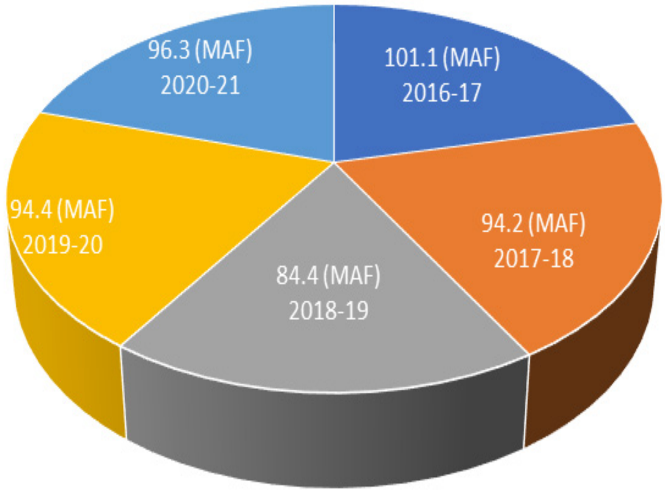

Figure 3: Caption: actual surface water availability during the last 5 years in Pakistan (2016-21).

Water management is a key area that needs attention for proper water use at the farm level. The conservation and use of water play a vital role in the country's agricultural economy (Bhatti *et al*., 2009). Water, agriculture, and food are directly linked (Pereira, 2017). Elimination of the country's freshwater reserves is limited and shrinking gradually for irrigated agriculture and reducing farmers' livelihoods. Improving Indus Basin System, which has a prominent role in irrigating land, is a big challenge (Basharat, 2019). The near future is a scarce resource for agricultural production under irrigated agriculture soon due to the exponentially growing population, and escalating requirements of the industry. Therefore, innovative water management technologies should be adopted in conjunction with soil moisture monitoring and smart climate agricultural practices to improve water productivity (Hasan *et al*., 2021).

This article examines the main causes of water scarcity in Pakistan's agriculture, the challenges posed by the water crisis, and its impacts on the agriculture sector, and explores potential solutions to mitigate this crisis in the general farming community and at the farm level. It will present various strategies and interventions to address the water crisis in agriculture. Addressing the water crisis in Pakistan requires a multifaceted approach involving policy reforms, technological advancements, and public awareness campaigns.

2. Roots of Water Scarcity

2.1 Development of water pollution

Insecticides, pesticides, city sewerage, industrial waste products, and fertilizers are polluting Pakistan's water sources (Ministry of Finance, 2007). Brackish and saline water is not fit for irrigation, so fresh water is decreasing over time (PWG, 2008). Out of the total available water 80% is polluted (Daud *et al*., 2017).

2.2 Limited water storage capacity

Storage capacity is limited to 13 MAF for 30 days and there is a need to store up to 145 MAF. The world's average storage is 120 days, four times longer than Pakistan's water storage capacity. The outdated distribution system in Pakistan wastes 24 MAFs annually (Salman, 2021). The country has no proper water harvesting system or water reservoirs against floods.

2.3 Unequal distribution of water

Distribution of irrigation water remains a major issue within different provinces. The distribution is according to supply based rather than need-based or cropping intensity. Historically, some areas remain in flood conditions (ADB, 2022), while others remain dry at the same time. Some landholders use more water at the start of the canal while others receive less water, causing disproportional distribution (Salman, 2021).

2.4 Mismanagement of water

Water theft directly from rivers and canals is another problem in agriculture. Strict actions of the Irrigation Department are indispensable in this regard. occasionally there is sufficient water, but mismanagement is one of the main problems. Most of the areas of the country face either water scarcity or flood situations (Salman, 2021). Alteration in groundwater modalities is another challenge by installing private tube wells without water resources available data (FAO, 2020).

3. Institutions involved in On-Farm Water Management in Pakistan

Various institutions are involved in the uplifting of water management are involved; however, prominent institutions are described here.

3.1 On-farm water management (OFWM)

Water Management Research Farm (WMRF) was established with the following objectives in line with the mission of the water management wing of the Agriculture Department envisaging more crop production per drop of water by following on-farm water management technologies, pilot testing, and indigenization of new water management techniques. Applied research is needed for the resolution of water issues faced by the farmers who require training and education on the adoption of OFWM, modern water conservation interventions, and the demonstration of improved on-farm water management practices that will empower growers to manage water more effectively and efficiently. Collaboration with national and international research institutions for joint research activities, in relevant disciplines, is paramount for success. At WMRF, practical interventions are being implemented using flood, drip, and sprinkler irrigation systems to evaluate the efficacy of monitoring soil moisture levels under multiple irrigation designs (OFWM, 2022). Punjab Agriculture Research Board (PARB) has also supported financially for research in this regard.

3.2 Role of international water management institute (IWMI)

Keeping in view the acute water shortage, climate change, and resilience of Pakistan, IWMI is working to improve agricultural productivity by enhancement in Water Use Efficiency (WUE) to meet the requirements of the United Nations Sustainable Development Goals (UNSDGs).

3.3 World bank initiative

Historically, the World Bank had a major contribution to water management by assisting in the construction of major dams e.g., Tarbela and Mangla, etc. The World Bank and the government of Pakistan support the goal of improving water use efficacy to cope with hunger, under the aim of sustainable development goals (SDGs) for supporting underdeveloped and developing countries for improving water use efficacy to cope with hunger, the world bank is supporting the government of Pakistan. Sindh On Farm Water Management (SOWMP) (The World Bank, 2015) and Punjab Irrigation Improvement Project (PIPIP) and Punjab Resilient and Inclusive Agriculture Transformation (PRIAT) initiatives are best contributed by World Bank as cost-sharing with farmers for water productivity improvement at on-farm levels (GoP, 2018b).

3.4 Asian development bank

Asian Development Bank (ADB) has also played a multi-functional role by supporting Pakistan in water management by conducting surveys and Water Resource Development Projects in Federally Administered Tribal Areas of Pakistan. It also assisted the National Disaster Management Authority (NDMA) of Pakistan in floods (ADB, 2022).

3.5 Japan international cooperation agency

Japan International Cooperation Agency (JICA) has played a key role in strengthening for improving water use efficiency at on-farm activities and irrigation efficiency by conducting various projects e.g., Punjab Irrigation System Improvement Project" (PISIP) (Japan International Cooperation Agency, 2022).

3.6 Food and agriculture organization

Food and Agriculture Organization (FAO) is also involved in the country's water resource and irrigation management strategies. A study accounting of water for improved management of water resources conducted by FAO from 18th January 2018 to 31st December 2019 provided a detailed analysis of water accounting in the country (FAO, 2020).

3.7 Legislative institutions

Federal and provincial institutes are vital to make water policies/ water acts for sustaining water resources.

4. Management Strategies for Alleviation of Water Crises

Following holistic management strategies for the alleviation of water resources decline is urgently needed at the time.

4.1 Awareness of farmers/public

The first and foremost strategy is to develop awareness among farmers and the general community about the upcoming water crisis and emphasize how critical adopting better practices is to fix the situation. Education is the cornerstone of awareness which should be provided to the public in the form of seminars, conferences, training events, etc. Action is needed from the farming community. We cannot achieve better water management practices until farmers understand the issues and are willing to act. For this purpose, seminars, conferences, etc. should be organized for capacity building (Tang *et al*., 2013; Sohail *et al*., 2022). Response to the upcoming water crisis in the country Faruqui (2007) suggested enhancement of the literacy percentage, careful water usage in agriculture, and controlling the growing population.

4.2 Research and demonstration

Since when to irrigate and how much to irrigate, the primary step to improve water use efficiency and water productivity is to focus on research water management techniques by designing research experiments. Without research, no effective technique could be introduced (Qureshi, 2019). Drought-resistant varieties should be grown to manage the water scarcity issue to improve water productivity.

4.3 Soil analysis through water infiltration apparatus

Conventionally double ring infiltrometer is used to test water percolation time in soil. Soil analysis is good for the retention ability of water in the soil which characterizes soil water dynamics. So, water could be applied accordingly by determining the soil intake family (Chari *et al*., 2021). Moreover, seepage in open water channel is measured by Seepage meter. It is also crucial to select plot sizes for irrigation by farmers in the field.

4.4 Selected tree plantation

To deal with climate change and global warming, massive tree plantation is required at suitable locations with carefully selected species (Lippke *et al*., 2021). Avoid the plantation of eucalyptus which transpire a high quantity of water (Abreu *et al*., 2022).

4.5 Infrastructure for water conservation

Unfortunately, the country's interest in building dams/ water reservoirs/ponds didn't gain priority. The lack of capital for the construction of dams further hindered progress. So, it is the need of the day to urgently take a step for dealing with this pitiable situation (Watto *et al*., 2021).

4.6 Irrigation scheduling

Based on crop water requirement by validated evapotranspiration (ET_o) and crop coefficient (Kc), another vital management is proper and timely irrigation at farms and water availability in canals is of utmost need (Hassan *et al*., 2020). Further at the farm level research is going on for specifying the Maximum Allowable Depletion levels (MAD) levels of crops required so that extent of irrigation could be understood.

4.7 Artificial intelligence/water management models

CLIMAT, aquacrop, and crop-watt models are a set of database software used to make irrigation schedules for crops/orchards at any location/season with any crop. Smart climate models can be used for accuracy in irrigation applications (George *et al*., 2000).

4.8 Water budgeting and accounting

Proper water budgeting and accounting eliminate uncertainty in water supplies is backbone for water management. Sources and total water required for crops according to the area, soil, and climatic conditions is another research-oriented field (Christ and Burritt, 2017).

4.9 Amendment in water accord/distribution

Justified water distribution is possible by demand and need-based distribution of water rather than supply-based distribution keeping in view the cropping intensity of certain areas under consideration.

4.10 Water-saving strategies

Following are advanced irrigation systems for saving water that also provides an active fertigation facility. However, all these irrigation systems are only efficient when topography, soil types, crops, and economic factors are kept in mind.

4.11 Land levelling

LASER land leveling (LLL) is an advanced form of Precision Land Leveling (PLL) (with no grade or variation less than ±20) is one of the vital technologies in this regard is leveling of agricultural lands (with zero slop) by laser land leveler (Tomar *et al*., 2020). Appropriate land levelling saves water up to 25% to 30% (Bhatt and Sharma, 2009).

4.12 Field border designing

To avoid the haphazard flow of water in the field, the zone/plot size of cultivated land depends on soil hydraulic properties (SHPs) (Kumar *et al*., 2022), and the discharge rate would be practiced. i.e., sandy soil requires a smaller zone size, while a large size of the zone is possible in clayey soil as loss of water will be less during flowing.

4.13 Sub-surface irrigation

Subsurface irrigation means irrigation below-soil surface pipes (near the soil surface) is most suitable for vegetable growing (Sakaguchi *et al*., 2019).

4.14 Water harvesting ponds

A profound impact of water harvesting ponds has been observed on the socio-economic status and food security of developing countries (Teshome *et* *al*., 2010; Malik *et al*., 2014). Annual rainfall has a potential of 50 billion cubic meters in the country, the third source of water. Store water for use on upcoming water shortage days. It collects rainwater where rains are a major source of water. This is a prerequisite in arid zones.

4.15 Lining of canals and water courses

To save water for percolation and seepage almost 50% canal lining is required. Above 50% would lead to a lowering water table in the soil as the recharge of water will decrease. Moreover, cleaning water courses is indispensable for the smooth and free flow of water.

4.16 Modified pipe outlets

Shape and type of Nakkas (large water outlet) at open water channel and Nakkos (small water outlet) in the field are important to save water being easier to open and close by lid than used conventionally. Pipe-type Nakkas are easy to close so offering less time to close the next outlet means saving irrigation water.

4.17 Agricultural water measurement

Most common method to measure the discharge of water is through flumes. Cut-throat flumes measure the discharge of water in the water channel which is vital for the exact measurement of applied water according to the need of the crop. Smart Flumes is an advanced version of conventional flumes which provide a real-time discharge of water flow in the watercourse at cellular phones. In both cases up head and down the head of fumes indicates discharge rate (Hu *et al*., 2014). Furthermore, water velocity/discharge is measured by a velocity meter and pigmy current methods in open water channel (Le coz *et al*., 2012). Floating method and pygmy are another approaches used in this regard. Tube-well discharge: Tube-well discharge is another important aspect with is measured roughly by the flow trajectory method or by using volumetric method.

Ultra-sonic digital flow meter: Digital flow meter proved to be very effective in measuring water discharge. So calculated amount of water required by the crop is ensured within due time (Awu *et al*., 2017).

4.18 High-efficiency irrigation system (HEIS)

Conventional irrigation has less than 40% efficiency. To enhance Water Use Efficiency (WUE) high efficiency is necessary for this scenario. According to season, area, and crop, various plans have been adopted for the future security of water (United States Department of Agriculture, 2022).

4.18.1 Drip irrigation

It is a kind of target irrigation that provides drop by drop of water for crops at their root zone, especially for orchards (Wang *et al*., 2023). It also filters water to some extent with sand and disk filters. Recently it is found most efficient water irrigation systems even in undulated lands (Kaya and Budak, 2022). An advancer form is automated drip irrigation where automation has been applied to the drip irrigation system which automatically irrigates when required (Guerbaoui *et al*., 2013). Now nano irrigation systems and responsive drip irrigation systems are advancement in this field as they irrigate as per need of the crop automatically with high precision.

4.18.2 Sprinkler irrigation

Raised sprinkler and surface sprinkler systems have been improved to save water. Overhead sprinkler systems spray nozzles are hung above plants and irrigate from a height above the plant canopy. Teixeira and Bastiaanssen (2012) described its suitability for on-farm water management for orchards.

4.18.3 Pivot irrigation system

For barren and vast areas with unlevelled lands central pivot (CP) irrigation from the top to downward like rainfall. However, it irrigates uniformly in circular fields mostly used for fodder in waste areas (Saeed *et al*., 2018). Best for converting barren lands to agricultural lands. A Pivot irrigation system could be perfectly used as precision irrigation by coordinating it with GIS and remote sensing (El Nahry, 2011).

4.18.4 Rain gun and water (hose) reels

It throws water with high-pressure water with a rain gun at the end of the reel. It moves its rain gun fixed at one end of the pipe where irrigation is required. After completion of irrigation its pipe rollback to a reel (Daccache *et al*., 2015).

4.19. Application of soil moisture sensors/gadgets

4.19.1. Handy soil moisture meter

Handy soil moisture meter is a portable device that quickly measures a digital value at any point in the field and at any depth. It is the most economical and easy way to assess moisture levels in the soil.

4.19.2 Enviro-SCAN

Enviro-SCAN is a highly efficient moisture sensing device for real-time measuring moisture levels at various soil depths, showing outcomes on a cellular phone/laptop device. It is an important tool for precision agriculture. It works on lands having zero slopes that make it restricted use (Robinson, 2009).

4.19.3 Chameleon Wi-Fi reader

A battery-operated device having three lights that measure moisture percentage at different levels with three probes with gypsum blocks that are inserted at different depths in the soil. It measures soil moisture by blinking lights of different colors concerning moisture levels at various depths (Fatima *et al*., 2022).

4.19.4 Full stop wetting front detector

Two different probes are inserted in the soil at different depths in root zones. The length of indicators depicts moisture levels in the soil. It also helps in fertigation plans (Adimassu *et al*., 2020).

4.19.5 Eddy covariance flux tower

It has ability to account for water, energy and carbon fluxes by incorporating all above-mentioned soil moisture gadgets along with advanced tools (Fang *et al*., 2024).

4.20 Miscellaneous strategies

4.20.1 Irrigation through gated pipes

Replacing water channel in the field, a metal/plastic pipes with manual opening and closing gates are altering the designs of flood irrigation. Automated gated pipes: An advanced form of gated pipes that automatically irrigate as and when required. It works by reducing conveyance losses of water in the furrow (Koech et al., 2010).

Piezometer: It shows the underground water table level live as and when turbine is extracting water and how much time require for recharge to maintain water table. It updates on mobile app or on PC by using SIM in the device for data transfer. Conductivity, Temperature and Depth (CTD) divers provide more information of underground water level and quality (Khosravi *et al*., 2024).

Remote well: The sensor operates for automatically turning off and on by using mobile phone application. We can make schedule for irrigation at any place provided that internet facility is available on sensor fixed with turbine and on mobile phone.

4.21 Geographic information system (GIS)

GIS helps in identifying suitable locations for irrigation projects by considering factors i.e., land elevation, proximity to water bodies, and soil characteristics. This aids in making informed decisions on where to implement irrigation infrastructure effectively. GIS allows the mapping and management of water resources, including rivers, lakes, ponds, and groundwater sources. By assessing the availability and proximity of water sources, farmers and irrigation authorities can plan irrigation systems and allocate water resources efficiently. GIS helps estimate crop water requirements by integrating climate data, soil properties, and crop-specific parameters. By understanding the water needs of different crops, farmers can optimize irrigation schedules and avoid over or under-watering, leading to improved water-use efficiency (Bwambale *et al*., 2022).

4.22 Remote sensing

Remote sensing helps assess the health and vigor of crops by measuring vegetation indices such as NDVI (Normalized Difference Vegetation Index). By monitoring crop growth and identifying stressed areas, farmers can adjust irrigation schedules, apply targeted interventions, and minimize water wastage. Remote sensing technologies can estimate soil moisture content over large areas. This information assists in optimizing irrigation schedules by providing insights into soil moisture levels, enabling farmers to irrigate only when necessary, reducing water usage, and conserving resources. Remote sensing can assess the effectiveness of irrigation practices by analyzing water distribution patterns, crop growth, and evapotranspiration rates. This data allows farmers and irrigation managers to evaluate system performance, identify inefficiencies, and optimize irrigation strategies (Singh, 2018; Bwambale *et al*., 2022).

5. Future Strategies and Government Policies

Discharge meters will be installed on tube wells for measuring the quantity of water discharged. It will save water to a certain extent. Artificial intelligence, mobile phone applications/software, and models are necessary as an IT (Information and Technology) approach that can predict water requirements before irrigation. Efficient and economical hydraulic strategies are necessary to make efforts feasible.

Reallocating canal water from areas with high water tables to areas with low water tables would prevent lands to become barren.

Conclusions and Recommendations

The major issues regarding jeopardizing food are developing due to water insecurity, inefficient irrigation practices with stagnant water productivity, and the lack and pricing of water management technologies are big challenges ahead. An integrated approach toward sustainable agricultural water management is indispensable to cope with the upcoming water crisis. Irrigation scheduling at the farm level is imperative for water productivity enhancement. Subsidizing and encouraging conventional/flood irrigation to high-efficiency practices is essential. Research and pilot testing of soil moisture measuring sensors must be primarily focused. The plant breeding institutes focus on developing drought-resistant varieties.

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Novelty Statement

This is the first article of this kind which comprehensively described review on innovative and sustainable agricultural water management strategies for Pakistan.

Author's Contribution

Mujahid Ali collected the resource/materials, Malik Muhammad Akram provided theme/background of the article, Emily Silverman critically reviewed and edited the ambiguities, Asif Iqbal described the advanced water management technologies, Muhammad Mohsan, and Haseeb Ahsan elaborated about remote sensing techniques used for water management.

Conflict of interest

The authors have declared no conflict of interest.

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