Scholars Journal of Agriculture and Veterinary Sciences

OPEN ACCESS

Abbreviated Key Title: Sch J Agric Vet Sci
ISSN 2348–8883 (Print) | ISSN 2348–1854 (Online)
Journal homepage: https://saspublishers.com

Advanced Agricultural Water Management in Pakistan: Integrative Approaches and Cutting-Edge Technologies to Combat Water Scarcity

Muhammad Asad Khan[1], Ayesha Noor[2], Seemal Tahir[3], Qudrat Ullah[4*], Muhammad Qasim[5], Irfan Haidri[6], Anam Shahzadi[7], Fatima Bibi[8]

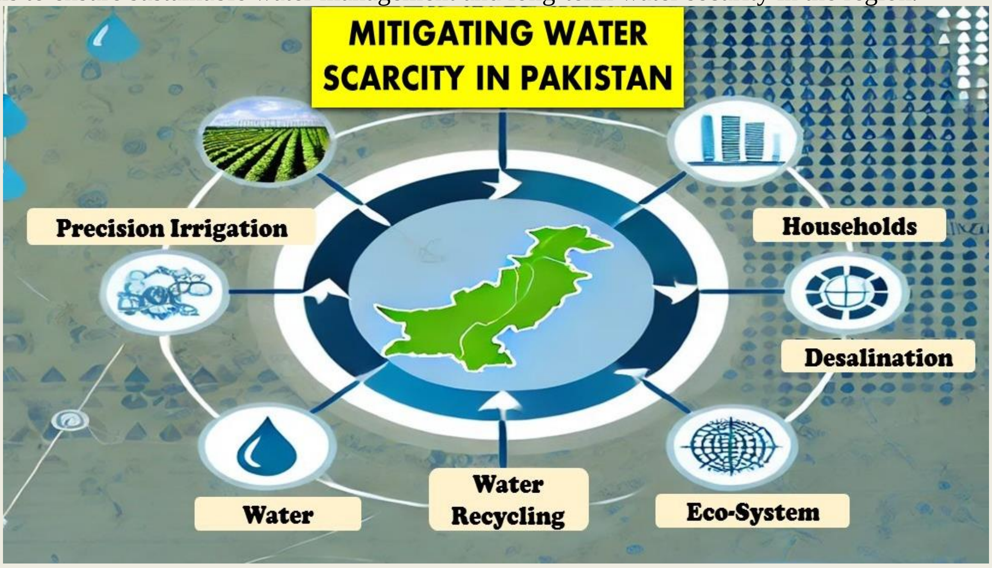
[1]Department of Agricultural Extension Education and Rural Development, University of Agriculture, Faisalabad, Punjab Pakistan
[2]Department of Biosciences, COMSATS University Islamabad, Sahiwal Campus, Punjab Pakistan
[3]Department of Botany, University of Agriculture, Faisalabad, Punjab Pakistan
[4]Department of Environmental Science, Government College University Faisalabad Punjab Pakistan
[5]College of Resources and Environment, Southwest University China
[6]Department of Environmental Science, Government College University Faisalabad, Punjab Pakistan
[7]Rangeland Research Institute, NARC
[8]Department of Botany, University of Agriculture Faisalabad Pakistan

DOI: https://doi.org/10.36347/sjavs.2024.v11i06.002 | **Received:** 28.07.2024 | **Accepted:** 31.08.2024 | **Published:** 07.09.2024

***Corresponding author:** Qudrat Ulla
Department of Environmental Science, Government College University Faisalabad Punjab Pakistan

Abstract | **Review Article**

This article explores the censorious challenge of water scarcity in Pakistan and presents a comprehensive analysis of several strategies and technological metamorphoses aimed at mitigating this issue. By examining precision irrigation, water recycling, desalination technologies, and ecosystem restoration, this article highlights their potential to escalate water use effectiveness and sustainability across key sectors such as agriculture, industry, and domestic use. It also evaluates the role of Integrated Water Resource Management (IWRM) and the National Water Policy, emphasizing the need for coordinated governance, public awareness, and education programs. The findings underline the importance of adopting a multi-sectoral approach, integrating advanced technologies, and fostering collaboration among stakeholders to address the growing water scarcity in Pakistan. The article concludes with recommendations for future research and policy reforms to ensure sustainable water management and long-term water security in the region.



Graphical Abstract

Keywords: Water scarcity, Pakistan, water management, technological metamorphosis, Integrated Water Resource Management (IWRM).

Citation: Muhammad Asad Khan, Ayesha Noor, Seemal Tahir, Qudrat Ullah, Muhammad Qasim, Irfan Haidri, Anam Shahzadi, Fatima Bibi. Advanced Agricultural Water Management in Pakistan: Integrative Approaches and Cutting-Edge Technologies to Combat Water Scarcity. Sch J Agric Vet Sci, 2024 Sep 11(6): 82-106.

INTRODUCTION

Water scarcity in Pakistan has reached a censorious juncture, posing an escalating challenge to the country's socio-economic stability and environmental sustainability. As a nation heavily dependent on freshwater resources, Pakistan is facing a speedily diminishing supply of these vital resources (Banerjee, 2023; Farooq, 2023). The per year per capita water availability, which was approximately 5,000 cubic meters in 1951, has alarmingly fallen to less than 1,000 cubic meters by 2022. This sharp fall-off places Pakistan in the category of a water-scarce country, according to the Falkenmark Water Stress Indicator (Ishaque *et al.*, 2023; KHAN[1] & KHAN, 2022). This situation is particularly dire when considering that the threshold for water scarcity is set at 1,000 cubic meters per capita per year, highlighting the severity of the current crisis (Zhang *et al.*, 2020).

This drastic reduction in water availability is exacerbated by the country's burgeoning population, which has surged past 230 million as of 2023 and is projected to grow by an additional 50% by 2050, potentially reaching 350 million (Gaaloul *et al.*, 2022). Such population growth is expected to further strain the already limited water resources, increasing the urging for water in all sectors, particularly in agriculture, which consumes an overwhelming 93% of the nation's total water resources (Nasreen & Ashraf, 2020). The agricultural sector, being the backbone of Pakistan's economy contributing approximately 19.2% to the GDP and employing around 39% of the labour force is acutely vulnerable to water shortages. This vulnerability directly threatens food security, as key crops like wheat, rice, and sugarcane are heavily dependent on irrigation (Schneider & Asch, 2020). The reduced water availability has already led to a fall in crop yields, with wheat production showing fluctuations of 10-30% in drought years, severely impacting both food availability and export revenues (Pequeno *et al.*, 2021).

The industrial sector, accounting for about 19% of the GDP and consuming roughly 5-6% of water resources, is also grappling with increasing water urgings. The textile industry, a major contributor to exports, requires outstanding water input for processes such as dyeing and finishing (Arbeiter & Velásquez, 2020). The growing water scarcity, coupled with pollution from industrial effluents, exacerbates the stress on water supplies. Water-intensive industries like textiles and food processing are facing operational disruptions, higher costs, and compliance challenges due to stricter environmental regulations aimed at curbing water pollution (Wang *et al.*, 2024).

The domestic sector, though consuming a smaller portion of the total water supply, is not immune to the effects of water scarcity. Urban zones, where the urging for potable water is swiftly increasing, are witnessing outstanding challenges in water supply (Hejazi *et al.*, 2023). In cities like Karachi and Lahore, up to 40% of the water supplied through municipal systems is off-track due to ageing infrastructure and leakage, resulting in a severe shortfall in water availability for household use. This scarcity is compounded by the contamination of water supplies with pollutants such as heavy metals, pathogens, and chemical residues, leading to public health crises, with waterborne diseases contributing to over 100,000 deaths yearly (Afzal *et al.*, 2016; Noureen *et al.*, 2022).

The situation is further aggravated by the effects of climate change, which are increasingly evident in Pakistan. The country is experiencing more frequent and severe droughts, with the number of dry years rising by 40% in the last two decades. Erratic precipitation patterns, with per year rainfall variability of up to 30%, have disrupted the hydrological cycle, leading to reduced river flows, decreased groundwater recharge, and diminished surface water storage (Adnan & Ullah, 2022; Khan *et al.*, 2024). The accelerated melting of glaciers in the northern regions, which contribute up to 70% of the Indus River's flow, causes a long-term threat to water availability. Glacial retreat, estimated at 0.3-0.5 meters per year, is reducing the natural reservoirs that sustain river flows during the dry season, exacerbating the water scarcity problem (Dar *et al.*, 2024).

Moreover, the compounding factors of over-extraction of groundwater, where extraction rates in zones like Punjab and Sindh exceed natural recharge rates by 20-30%, and the pollution of water bodies from industrial, agricultural, and domestic sources have further strained the country's water resources (Le Quesne *et al.*, 2010). Groundwater levels are dropping by up to 1.5 meters yearly in some regions, leading to the salinization of aquifers and the intrusion of saline water, rendering them unsuitable for agricultural or domestic use (Kumar, 2023).

Pakistan can effectively address its groundwater depletion by implementing a comprehensive approach that combines managed aquifer recharge (MAR), strict regulation and monitoring of groundwater extraction, and the promotion of water-efficient irrigation techniques such as drip irrigation and laser land levelling (Mainuddin *et al.*, 2021a, 2021b). Encouraging the cultivation of drought-resistant, less water-intensive crops, along with providing economic incentives for sustainable agricultural practices, is vital. Community-based water management and public awareness campaigns can foster local stewardship of groundwater resources. Additionally, the recycling and reuse of treated wastewater for irrigation and industrial purchases, coupled with the construction of climate-resilient infrastructure like recharge structures, can outstandingly reduce the reliance on groundwater. Integrating these efforts within an overarching Integrated Water Resource Management (IWRM) framework, supported by institutional strengthening, research, and international collaboration, is crucial for reversing the trends of groundwater over-extraction and ensuring long-term water security in Pakistan (Mujtaba *et al.*, 2024).

This review systematically explores and evaluates a comprehensive range of strategies to mitigate water scarcity in Pakistan, grounded in evidence-based research and leveraging scientific methodologies to estimate the effectiveness of interventions across multiple sectors. By focusing on agriculture, industry, domestic water use, environmental conservation, policy, and technological metamorphosis, the review provides an integrated approach to water management, emphasizing sustainable practices, efficient resource allocation, and the implementation of advanced technologies to escalate water use effectiveness. The analysis considers the socio-economic impacts of water scarcity and the feasibility of proposed solutions within Pakistan's socio-political context. The article begins with an in-depth analysis of agricultural water management, including precision irrigation, drought-resistant crops, and water pricing models, supported by quantitative data on water use effectiveness. It then examines industrial water use, exploring water recycling, cleaner production technologies, and regulatory frameworks, with data tables and bar graphs illustrating their impact on reducing water usage. The third section highlights domestic water conservation, urban water supply effectiveness, rainwater harvesting, and decentralized wastewater treatment, with a pie chart showing water usage distribution across domestic activities. Environmental conservation and ecosystem restoration are discussed in the fourth section, focusing on wetlands and river restoration, sustainable groundwater management, and climate change adaptation, supported by a heatmap estimating river basin vulnerability. The fifth section explores policy and governance, including Integrated Water Resource Management (IWRM) and the National Water Policy, along with public awareness and education, supported by a radar chart estimating policy effectiveness. The sixth section delves into technological metamorphosis, such as smart water management systems, desalination technologies, and remote sensing, with a line graph illustrating trends in water availability and technology adoption. The article concludes by summarizing key findings and offering recommendations for future research and policy, emphasizing the need for an integrated, multi-sectoral approach and collaboration among government, industry, and local communities to address water scarcity in Pakistan and similar regions.

Agricultural Water Management Strategies

Water management in agriculture is censorious for Pakistan, where the sector consumes approximately 93% of the country's freshwater resources, as reported by the Food and Agriculture Organization (FAO) in 2022 (Assan *et al.*, 2022). Given the substantial contribution of agriculture to Pakistan's GDP, which stood at 19.2% in 2021 according to the Pakistan Bureau of Statistics, the sustainability of this sector is intrinsically tied to the efficient use of water resources. In response to growing water scarcity, several scientific and technological strategies have been developed to escalate water use effectiveness in agriculture, with precision irrigation techniques, the development of drought-resistant crops, and water pricing models being at the forefront (Islam *et al.*, 2023).

Precision Irrigation Techniques

One of the most outstanding evolutions in agricultural water management is the adoption of precision irrigation techniques, which have shown considerable potential in reducing water use while maintaining or even increasing crop yields (Angelakıs *et al.*, 2020). Drip irrigation, in particular, is a scientifically validated method that delivers water directly to the plant roots through a network of valves, pipes, tubing, and emitters. This method has been shown to improve water use effectiveness by up to 90% compared to traditional flood irrigation, which often results in outstanding water losses due to evaporation, runoff, and deep percolation (Bhavsar *et al.*, 2023). A study by Ul Hussan et al. (2023) indicated that drip irrigation could reduce water consumption by 30-70% depending on the crop and environmental conditions. In Pakistan, where crops like wheat, rice, and sugarcane are heavily reliant on irrigation, the widespread adoption of drip irrigation could potentially save billions of cubic meters of water yearly.

The implementation of laser land levelling is another precision technique that has garnered attention for its ability to escalate irrigation effectiveness. Laser land levelling involves the use of laser-guided equipment to level the field, ensuring uniform distribution of water across the entire plot. This method not only reduces water wastage by up to 25-30%, as reported by Tomar *et al.*, (2020) but also improves crop yields by ensuring that water reaches all zones of the field evenly. In the Punjab province, where agricultural productivity is crucial, laser land levelling could be a game-changer in optimizing water use. The combination of drip irrigation and laser land levelling presents a powerful master plan for conserving water, particularly in regions where water resources are becoming increasingly scarce.

Development of Drought-Resistant Crops

In parallel with the evolution of irrigation techniques, the development of drought-resistant crop varieties through genetic modification and conventional breeding approaches is a censorious zone of focus. Drought-resistant crops are engineered or bred to withstand water stress by enhancing their physiological and biochemical responses to drought conditions. For example, crops can be genetically modified to have deeper root systems, which allow them to access water from deeper soil layers, or to have improved stomatal regulation, reducing water loss through transpiration.

Research studies by Siddiqui *et al.*, (2021) and Raza *et al.*, (2023) have demonstrated that drought-resistant varieties of wheat and maize can maintain yields with up to 50% less water compared to traditional varieties.

In Pakistan, where the Indus River system provides the primary water source for irrigation, the introduction of drought-resistant crops could outstandingly mitigate the impact of water scarcity. The International Maize and Wheat Improvement Center (CIMMYT) has been working on developing drought-tolerant wheat varieties specifically suited for South Asian climates (Sukumaran *et al.*, 2021). These varieties have shown a yield increase of 20-30% under water-limited conditions, offering a viable solution to the challenges posed by water scarcity. Furthermore, conventional breeding programs in Pakistan have also focused on selecting and cross-breeding native varieties that exhibit natural drought resistance, further enhancing the resilience of the agricultural sector.

Water Pricing Models and Economic Incentives

Beyond technological and biological interventions, economic strategies such as water pricing models and incentives play a crucial role in managing agricultural water use. The concept of tiered water pricing, where the cost of water increases with higher levels of consumption, is based on the economic principle of urging elasticity. This model incentivizes farmers to use water more efficiently, as higher consumption results in increased costs. Research by Li *et al.*, (2023) suggests that implementing tiered water pricing in agriculture can reduce water use by 15-20% without outstandingly impacting crop production.

In the context of Pakistan, where water is often underpriced or provided at a flat rate, the introduction of a tiered pricing model could motivate farmers to adopt water-saving technologies and practices. The economic incentive to reduce water consumption could also drive investment in precision irrigation systems, drought-resistant crops, and other water-efficient technologies (Ahmed *et al.*, 2024). Additionally, the revenue generated from water pricing could be reinvested into water infrastructure, further enhancing the effectiveness and sustainability of the agricultural sector (Siddiqi *et al.*, 2024).

Economic incentives could also be extended to the promotion of water-efficient crops. Subsidies for crops that require less water, coupled with penalties for water-intensive crops, could shift agricultural practices toward more sustainable options. For instance, shifting from water-intensive crops like rice and sugarcane to less water-urging crops such as pulses or sorghum could alleviate pressure on water resources while maintaining agricultural output. This master plan would require a careful balancing of economic, environmental, and social considerations, but the potential advantages in terms of water conservation are substantial (Zhang & Oki, 2023).

Integrated Water Management Practices

The integration of precision irrigation techniques, the development of drought-resistant crops, and economic incentives under a comprehensive water management framework are vital for maximizing the impact of these strategies. Integrated Water Resource Management (IWRM) emphasizes the coordinated development and management of water, land, and related resources to maximize economic and social welfare without compromising the sustainability of ecosystems (Kalogiannidis *et al.*, 2023). In agriculture, this approach involves aligning irrigation practices with crop selection, pricing models, and technological metamorphosis to create a cohesive and sustainable water management system (ENERGY, 2023).

The adoption of IWRM in Pakistan's agricultural sector could escalate the resilience of the sector to water scarcity while ensuring the equitable distribution of water resources. This approach would require the collaboration of government agencies, research institutions, and the agricultural community to develop and implement policies that support sustainable water use. By integrating scientific knowledge with practical applications, IWRM could lead to outstanding improvements in water use effectiveness and agricultural productivity.

Challenges and Hurdles to Implementation

Despite the clear advantages of precision irrigation, drought-resistant crops, and economic incentives, several challenges and hurdles must be addressed to ensure their successful implementation. One of the primary challenges is the initial cost of adopting new technologies such as drip irrigation and laser land levelling. While these technologies offer long-term savings and increased productivity, the upfront investment can be prohibitive for smallholder farmers, who constitute an outstanding portion of Pakistan's agricultural sector (Faazal *et al.*, 2023; Singh; Ullah, Qasim, *et al.*, 2024). Financial support through government subsidies, low-interest loans, or public-private partnerships could help overcome this barrier and facilitate widespread adoption.

Another challenge is the need for capacity building and education among farmers. The successful implementation of precision irrigation and the cultivation of drought-resistant crops require a deep understanding of these technologies and practices. Extension services, training programs, and demonstration projects are vital to equip farmers with the knowledge and skills needed to adopt and maintain this metamorphosis (Serote et al., 2023). Furthermore, the effectiveness of water pricing models depends on accurate measurement and monitoring of water usage, which requires robust infrastructure and governance mechanisms.

Environmental and Ecological Considerations

While the focus of agricultural water management is often on increasing effectiveness and productivity, it is crucial to consider the environmental and ecological impacts of these strategies. The overuse of irrigation, even with efficient systems like drip irrigation, can lead to soil salinization, which reduces soil fertility and crop yields over time. Moreover, the development of drought-resistant crops must be carefully managed to avoid unintended consequences, such as the displacement of native plant species or the disruption of local ecosystems (Fatima *et al.,* 2024; Nouri *et al.,* 2023).

Environmental monitoring and statements should be an integral part of any agricultural water management master plan to ensure that the long-term health of the soil and ecosystems is maintained. Sustainable practices, such as crop rotation, organic farming, and the use of natural fertilizers, should be promoted alongside technological metamorphosis to create a holistic approach to water management that supports both agricultural productivity and environmental stewardship (Mallareddy *et al.,* 2023).

Potential Impact on Food Security

The successful implementation of precision irrigation, drought-resistant crops, and water pricing models has the potential to outstandingly escalate food security in Pakistan. By improving water use effectiveness, these strategies can increase agricultural productivity and reduce the vulnerability of crops to water scarcity. This is particularly important in a country where food security is closely linked to the availability of water for irrigation (Muzammil *et al.,* 2020; Waseem, Abbas, *et al.,* 2023). The adoption of these strategies could lead to higher crop yields, more stable food supplies, and reduced dependence on food imports, thereby strengthening national food security.

Furthermore, the cultivation of drought-resistant crops could provide a buffer against the impacts of climate change, which is expected to exacerbate water scarcity in the coming decades. By ensuring that crops can thrive under water-limited conditions, this metamorphosis could help safeguard food production in the face of changing environmental conditions (Mushtaq *et al.,* 2024).

Economic Implications

The economic implications of adopting precision irrigation, drought-resistant crops, and water pricing models are outstanding. On the one hand, these strategies can lead to cost savings for farmers by reducing water consumption and increasing crop yields. On the other hand, the initial investment required for these technologies may pose a financial burden, particularly for smallholder farmers. However, the long-term economic advantages, including increased agricultural productivity, reduced water costs and escalated food security, outweigh the initial expenses (Haidri *et al.,* 2024; Mushtaq *et al.,* 2024).

Moreover, the introduction of water pricing models can generate revenue that can be reinvested in the agricultural sector, supporting the development of infrastructure, research, and extension services. This revenue can also be used to subsidize the adoption of water-efficient technologies, making them more accessible to all farmers (Lakhiar *et al.,* 2024). The economic advantages of these strategies extend beyond the agricultural sector, contributing to broader economic growth and development in Pakistan.

Social and Cultural Considerations

The adoption of new agricultural practices and technologies is often influenced by social and cultural factors. In Pakistan, where agriculture is deeply rooted in tradition, there may be resistance to change, particularly among older generations of farmers. Social norms, cultural beliefs, and traditional practices can all play a role in shaping attitudes toward new technologies and water management practices (Jin *et al.,* 2022; Ummer *et al.,* 2023).

To address these challenges, it is vital to engage with local communities and involve them in the decision-making process. Participatory approaches that include farmers, community leaders, and other stakeholders can help build trust and ensure that new practices are culturally acceptable and aligned with local values. Education and awareness campaigns that highlight the advantages of precision irrigation, drought-resistant crops, and water pricing models can also help overcome resistance and motivate adoption (Muhammad & Hariyati, 2021).

Future Research and Development

While outstanding progress has been made in the development of precision irrigation techniques, drought-resistant crops, and water pricing models, there is still much to learn and improve. Future research should focus on optimizing these technologies for the specific conditions of Pakistan, taking into account factors such as soil type, climate, and water availability (Ullah, Munir, *et al.,* 2024). Additionally, research should explore the potential of emerging technologies, such as remote sensing and artificial intelligence, to further escalate water use effectiveness in agriculture (Violino *et al.,* 2023).

Collaborative research involving universities, research institutions, government agencies, and the private sector is vital to drive innovation and ensure that new technologies are developed and implemented in a way that is both scientifically sound and practically feasible. Continued investment in research and development is crucial for advancing agricultural water management and addressing the challenges of water scarcity in Pakistan (Arshed *et al.,* 2022).

Therefore, the adoption of precision irrigation techniques, the development of drought-resistant crops, and the implementation of water pricing models represent censorious strategies for addressing water scarcity in Pakistan's agricultural sector. These strategies, supported by scientific research and technological innovation, have the potential to outstandingly escalate water use effectiveness, increase agricultural productivity, and strengthen food security. However, their successful implementation will require overcoming challenges related to cost, capacity building, environmental impacts, and social acceptance. By integrating these strategies within a comprehensive water management framework and supporting them with research, education, and policy, Pakistan can make outstanding progress toward sustainable agriculture and long-term water security.

Table 1: Water Use Effectiveness of Several Irrigation Techniques in Pakistan's Major Crops

Crop	Traditional Flood Irrigation (m^3/ton)	Drip Irrigation (m^3/ton)	Laser Land Leveling (m^3/ton)	Effectiveness Gain with Drip Irrigation (%)	Effectiveness Gain with Laser Land Leveling (%)
Wheat	1,500	900	1,050	40%	30%
Rice	3,000	1,800	2,100	40%	30%
Sugarcane	4,500	2,700	3,150	40%	30%
Maize	2,000	1,200	1,400	40%	30%

Note: The percentage effectiveness gains are calculated relative to the traditional flood irrigation method. Drip irrigation and laser land levelling show outstanding improvements in water use effectiveness, making them viable options for reducing water consumption in Pakistan's agriculture.

This table provides a comparative analysis of the water use effectiveness (WUE) of different irrigation techniques applied to Pakistan's major crops, including wheat, rice, sugarcane, and maize. The table highlights the effectiveness gains attained through modern irrigation methods such as drip irrigation and laser land levelling compared to traditional flood irrigation. The values are expressed in terms of cubic meters of water used per ton of crop produced (m^3/ton), reflecting the amount of water required to produce a unit of each crop. The data demonstrates how precision irrigation techniques can outstandingly reduce water usage, thereby contributing to water conservation and sustainability in the agricultural sector.

Industrial Water Use and Effectiveness

The industrial sector in Pakistan, though consuming a smaller portion of the nation's total water resources compared to agriculture, plays an outstanding role in the overall water urging, particularly in urban and peri-urban zones. The sector is responsible for approximately 5-6% of the total freshwater withdrawal in Pakistan, according to estimates by the World Bank. With the ongoing industrialization and urban expansion, this figure is expected to rise, further exacerbating the challenges of water scarcity (Baig *et al.*, 2024; Chapagain *et al.*, 2022). Therefore, enhancing water use effectiveness within industries through water recycling, cleaner production technologies, and robust regulatory frameworks is crucial for sustainable water management.

Water Recycling and Reuse in Industry

Water recycling and reuse represent censorious strategies for reducing freshwater withdrawal in industrial processes. These practices involve treating wastewater generated from industrial activities to a quality that allows it to be reused within the same or different industrial processes. The implementation of water recycling technologies such as membrane filtration, reverse osmosis, and advanced oxidation processes has been shown to outstandingly reduce water consumption. For instance, membrane filtration, which includes microfiltration, ultrafiltration, and Nano filtration, can recover up to 90% of the water used in industrial processes, as documented in research studies by Ahmad *et al.*, (2022).

To quantify the advantages, consider an industry that uses 1,000 cubic meters of water daily, with traditional methods leading to 800 cubic meters of wastewater. Implementing a membrane filtration system that recycles 90% of the wastewater would reduce freshwater withdrawal to just 200 cubic meters daily, a reduction of 80%. Mathematically, the effectiveness gain (η) from water recycling can be expressed as:

$$\eta = \left(\frac{\text{Water Recycled}}{\text{Total Water Used}}\right) \times 100$$

For this example, $\eta = \left(\frac{800\ \text{m}^3}{1000\ \text{m}^3}\right) \times 100 = 80\%.$

The textile industry, one of Pakistan's largest and most water-intensive sectors, can particularly benefit from water recycling technologies. Textile production involves processes such as dyeing, finishing, and washing, which are highly water-dependent. By integrating water recycling systems, textile factories can outstandingly reduce their water footprint. Research studies have shown that water reuse in textile operations can lower water consumption by up to 50%, while also reducing the environmental impact by minimizing wastewater discharge.

Cleaner Production Technologies

Cleaner production technologies (CPT) offer another viable solution for improving water use effectiveness in industry. These technologies focus on reducing waste and emissions by optimizing processes and utilizing resources more efficiently (Abbas *et al.*, Dinga & Wen, 2022). In the context of water use, CPT in the textile and manufacturing sectors involves adopting techniques that minimize water usage and escalate the effectiveness of water-intensive processes.

For example, low-liquor ratio dyeing machines, which operate with a lower ratio of water to fabric, have been shown to reduce water consumption by up to 50% compared to conventional dyeing machines. Similarly, the use of closed-loop water systems in industries can recover and reuse nearly all the water used in cooling and other processes, thereby drastically reducing the need for freshwater intake (Chakraborty & Ahmad, 2022; Morseletto *et al.*, 2022). The equation governing the reduction in water consumption (W_r) using such systems can be expressed as:

$$W_r = W_0 \times (1 - E)$$

Where W_0 is the original water usage and E is the effectiveness of the cleaner production technology (expressed as a decimal). For an industry originally using 1,000 cubic meters of water with a cleaner production effectiveness of 50% (E=0.5), the reduction in water use would be:

$$W_r = 1000 \times (1 - 0.5) = 500\,\text{m}^3$$

Thus, the implementation of CPT can lead to substantial reductions in water consumption, directly contributing to the sustainability of industrial operations (Villain-Gambier *et al.*, 2020).

Regulatory Frameworks for Industrial Water Management

The effectiveness of water recycling and cleaner production technologies is heavily influenced by the regulatory environment in which industries operate. Regulatory frameworks for industrial water management in Pakistan have historically been weak, with limited enforcement of existing laws. The Pakistan Environmental Protection Act (PEPA) of 1997, which governs the discharge of pollutants into water bodies, includes provisions for the treatment and reuse of industrial wastewater (Parveen & Khan, 2023). However, the enforcement of these regulations remains an outstanding challenge due to limited resources, lack of monitoring infrastructure, and insufficient penalties for non-compliance.

A censorious evaluation of the existing regulatory frameworks reveals several gaps that hinder effective water management in the industrial sector. For instance, there is a lack of comprehensive water pricing mechanisms that would incentivize industries to adopt water-efficient technologies. Currently, water tariffs for industrial consumers in Pakistan are low, failing to reflect the true cost of water extraction and treatment. Introducing tiered water pricing, where the cost increases with higher consumption, could motivate industries to invest in water-saving technologies and reduce overall water use (Khan *et al.*, 2022).

Furthermore, the establishment of stringent effluent standards and regular monitoring of industrial wastewater discharge is vital for ensuring that industries comply with environmental regulations. The introduction of real-time monitoring systems, coupled with stricter penalties for violations, could outstandingly improve compliance rates. These systems could utilize advanced technologies such as remote sensing and IoT (Internet of Things) devices to track water usage and effluent quality, providing data that can be used to enforce regulations more effectively (Salam, 2024).

Economic and Environmental Impacts

The adoption of water recycling, cleaner production technologies, and robust regulatory frameworks can have substantial economic and environmental advantages. Economically, these measures can reduce operational costs for industries by decreasing the need for fresh water and lowering wastewater treatment expenses. For example, industries that implement water recycling technologies may see a reduction in water procurement costs by up to 60%, depending on the scale and effectiveness of the system (Faragò *et al.*, 2021; Radcliffe & Page, 2020).

Environmentally, reducing industrial water consumption and minimizing wastewater discharge contribute to the preservation of freshwater resources and the protection of aquatic ecosystems. The reduction in pollutants entering water bodies helps maintain water quality, which is crucial for both human consumption and the health of ecosystems. By mitigating the environmental impact of industrial activities, these strategies also support Pakistan's commitments to international environmental agreements, such as the Sustainable Development Goals (SDGs), particularly Goal 6, which focuses on clean water and sanitation (Mujtaba *et al.*, 2024).

Challenges and Hurdles to Implementation

Despite the clear advantages of water recycling, cleaner production technologies, and regulatory enforcement, several challenges must be addressed to ensure successful implementation. One of the primary hurdles is the high initial capital investment required for installing advanced water treatment and recycling systems. Many industries, particularly small and medium enterprises (SMEs), may lack the financial resources to invest in these technologies without external support. Government subsidies, low-interest loans, and financial incentives could help alleviate this barrier and motivate wider adoption (Indrawati, 2020).

Another challenge is the need for technical expertise and capacity building. The operation and maintenance of advanced water recycling systems and cleaner production technologies require specialized knowledge and skills. Training programs and technical assistance initiatives are vital to equip industry personnel with the necessary competencies to manage these systems effectively.

Case Research Studies and Best Practices

Examining case research studies of successful water management initiatives in other countries can provide valuable insights for Pakistan. For instance, Israel, a global leader in water recycling, treats nearly 90% of its wastewater for reuse in agriculture and industry (Miarov *et al.,* 2020). The success of Israel's water recycling program is attributed to a combination of advanced technology, strong regulatory frameworks, and public awareness campaigns. Adopting similar approaches in Pakistan, tailored to the local context, could yield outstanding improvements in industrial water use effectiveness (Dai, 2021; Gulati *et al.*, 2021).

In addition, collaborations with international organizations and partnerships with the private sector can facilitate the transfer of knowledge and technology. Public-private partnerships (PPPs) have been particularly effective in financing and implementing large-scale water recycling projects in countries like Singapore and the United States (Shambaugh & Joshi, 2021). These partnerships can provide the financial and technical resources needed to scale up water management initiatives in Pakistan.

Future Directions and Research Needs

Looking forward, there is a need for ongoing research and innovation in industrial water management technologies. Developing more cost-effective and energy-efficient water recycling systems is crucial for ensuring that these technologies are accessible to all industries, regardless of size or financial capacity. Research should also focus on the integration of renewable energy sources, such as solar and wind power, into water recycling processes to reduce the carbon footprint of these systems.

Moreover, there is a need for research on the social and behavioural aspects of water use in industry. Understanding the factors that influence industrial decision-making regarding water use and conservation can inform the design of policies and interventions that motivate sustainable practices. Engaging with industry stakeholders to identify hurdles and opportunities for water effectiveness can also help tailor solutions to the specific needs and contexts of different industries.

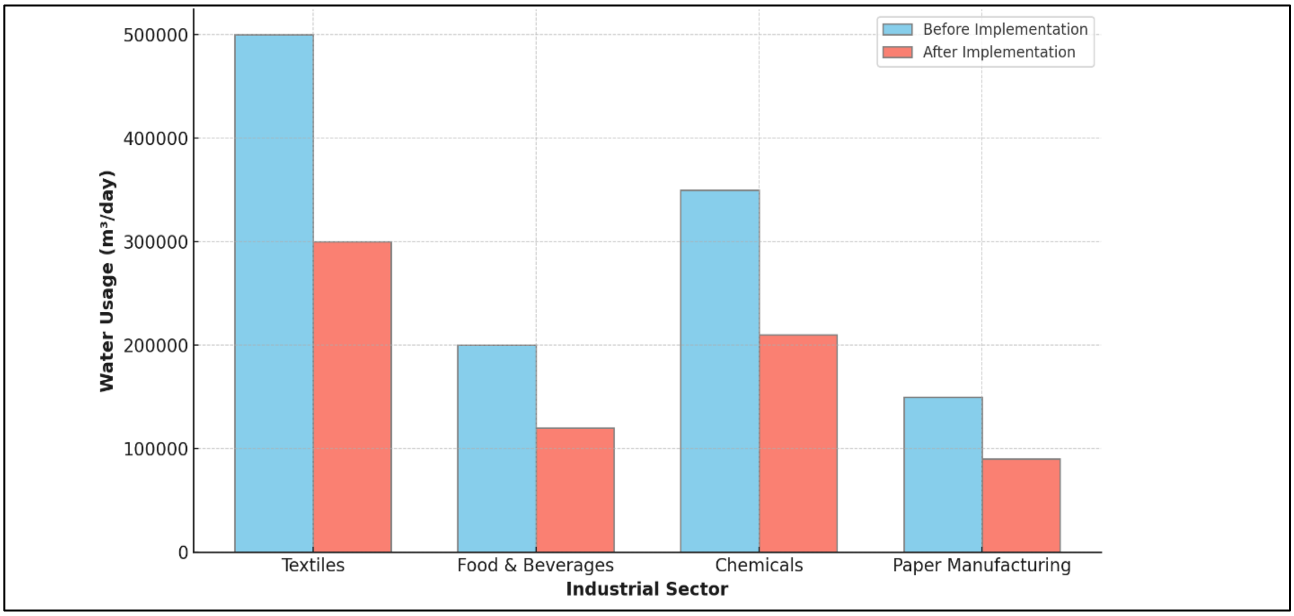
Therefore, enhancing industrial water use effectiveness in Pakistan is vital for addressing the country's growing water scarcity challenges. Water recycling and reuse, cleaner production technologies, and effective regulatory frameworks are key strategies that can outstandingly reduce industrial water consumption and environmental impact. However, successful implementation requires addressing financial, technical, and regulatory hurdles, as well as fostering collaboration between the public and private sectors. By prioritizing sustainable water management in industry, Pakistan can safeguard its water resources for future generations while supporting economic growth and environmental protection.

Table 2: Water Consumption and Recycling Rates in Key Industrial Sectors in Pakistan

Industrial Sector	Daily Water Consumption (m^3)	Percentage of Water Recycled (%)	Recycled Water Volume (m^3)	Potential Water Savings with Increased Recycling (%)
Textiles	500,000	25%	125,000	40%
Food and Beverages	200,000	15%	30,000	50%
Chemicals	350,000	20%	70,000	45%
Paper Manufacturing	150,000	10%	15,000	60%

Note: The "Potential Water Savings with Increased Recycling" column estimates the additional percentage of water that could be saved if recycling rates were escalated through technological upgrades and better water management practices.

This table presents a detailed comparison of water consumption and recycling rates across key industrial sectors in Pakistan, including textiles, food and beverages, chemicals, and paper manufacturing. The table provides insights into the volume of water consumed daily by each sector (in cubic meters) and the percentage of that water which is recycled through several technological processes. The data highlights the potential for water savings through increased recycling efforts, emphasizing the need for further investment in water-efficient technologies within these industries.



Graph 1: Comparison of Water Usage before and After Implementation of Cleaner Production Technologies

This bar graph visually compares the water usage in key industrial sectors in Pakistan before and after the implementation of cleaner production technologies. The graph shows the daily water consumption (in cubic meters) for each sector, with the blue bars representing the water usage before implementing cleaner technologies and the red bars showing the reduced water usage after implementation. The difference in bar height across each sector highlights the outstanding reductions in water consumption attained through these technologies. This graph shows how the adoption of cleaner production technologies can lead to substantial water savings in industries such as textiles, food and beverages, chemicals, and paper manufacturing. This visual representation underlines the importance of investing in water-efficient technologies to escalate sustainability and mitigate the impacts of water scarcity in Pakistan's industrial sectors.

Domestic Water Conservation

Domestic water conservation has emerged as a crucial zone of focus in addressing water scarcity, particularly in promptly urbanizing regions of Pakistan. The domestic sector, while not the largest consumer of water compared to agriculture and industry, plays an outstanding role in the overall urging for freshwater resources (Waseem, Mutahir Ullah Ghazi, *et al.*, 2023). With an estimated population of over 230 million and growing urban centres, the pressures on domestic water supplies are intensifying. This section examines three key strategies for enhancing water conservation at the household level, improving urban water supply effectiveness, implementing rainwater harvesting systems, and adopting decentralized wastewater treatment technologies.

Urban Water Supply Effectiveness

Urban water supply systems in Pakistan are distinguished by outstanding inefficiencies, with water losses due to leakage and poor distribution management being major concerns. Estimates indicate that up to 30-40% of water supplied through municipal systems is off-track before it reaches the end-consumers, primarily due to ageing infrastructure, faulty connections, and inadequate maintenance (Khalid *et al.*, 2024). In cities like Karachi and Lahore, where the urging for water far exceeds the supply, these losses exacerbate the challenges of water scarcity.

Technological evolution offers viable solutions for improving the effectiveness of urban water supply systems. One such solution is the adoption of smart water management systems, which utilize real-time data from sensors installed throughout the water distribution network. These sensors can detect leaks, monitor pressure levels, and estimate water quality, enabling prompt maintenance and reducing water loss. Implementing such systems in urban zones can lead to a reduction in water losses by up to 20-25%, according to research studies conducted in comparable urban settings globally. The cost-effectiveness of these systems has also been demonstrated, with the potential for outstanding savings in both water and energy costs.

Mathematically, the effectiveness improvement (η) due to leak detection can be expressed as:

$$\eta = \frac{\text{Water Saved}}{\text{Water Supplied}} \times 100$$

For instance, if an urban water supply system delivers 500,000 cubic meters of water per day and smart

management systems reduce losses by 20%, the water saved would be:
Water Saved=500,000 × 0.20=100,000 m^3 / day

This translates into an outstanding conservation of precious water resources that can be redirected to meet the needs of underserved communities.

Rainwater Harvesting

Rainwater harvesting is another effective master plan for domestic water conservation, particularly in zones where municipal water supplies are unreliable or insufficient. This technique involves capturing and stockpiling rainwater from rooftops and other surfaces for later use in domestic activities such as irrigation, flushing toilets, and even drinking after appropriate treatment. The potential for rainwater harvesting in Pakistan is considerable, given the country's diverse climate and seasonal rainfall patterns (Hussain *et al.*, 2023).

For instance, in regions like Punjab and Sindh, where the average per year rainfall ranges between 300 to 600 millimeters, a typical household with a roof zone of 100 square meters could potentially harvest between 30,000 to 60,000 liters of water yearly (Hannan *et al.*, 2021). This water can be stored in tanks and used during dry periods, outstandingly reducing the dependence on groundwater and municipal supplies. The effectiveness of rainwater harvesting systems (E_{RWH}) can be calculated using the formula:

$$E_{\mathrm{RWH}} = \frac{\text{Rainfall (mm/year)} \times \text{Catchment Area (m}^2\text{)}}{\text{Runoff Coefficient}} \times \text{Collection Efficiency}$$

Assuming a runoff coefficient of 0.85 and collection effectiveness of 90%, a household in a zone receiving 500 mm of rainfall per year with a 100 m² roof could collect:

$$E_{\mathrm{RWH}} = \frac{500 \times 100}{0.85} \times 0.90 = 52,941 \text{ liters/year}$$

Such systems can be implemented at relatively low costs and with minimal technical expertise, making them accessible to a wide range of households, both in urban and rural settings.

Decentralized Wastewater Treatment

The concept of decentralized wastewater treatment has gained traction as a sustainable solution for managing household-level water use. Traditional centralized wastewater treatment plants, while effective, are often costly to build and maintain, particularly in developing countries where infrastructure development may lag behind population growth. Decentralized systems, on the other hand, offer a flexible and scalable alternative that can be tailored to the specific needs of individual communities or even single households.

Two prominent technologies in decentralized wastewater treatment are bioreactors and constructed wetlands. Bioreactors are engineered systems that use microbial processes to treat wastewater. These systems can be designed as anaerobic or aerobic, depending on the specific requirements of the treatment process. Anaerobic bioreactors, for example, are effective in reducing biochemical oxygen urging (BOD) and chemical oxygen urging (COD) by up to 90%, making the treated water suitable for non-potable uses such as irrigation or toilet flushing (Huang *et al.*, 2024). The treatment effectiveness (E_t) of a bioreactor can be described by the equation:

$$E_t = \left(\frac{\text{Inlet Concentration} - \text{Outlet Concentration}}{\text{Inlet Concentration}}\right) \times 100$$

If the inlet concentration of BOD is 300 mg/L and the outlet concentration after treatment is reduced to 30 mg/L, the effectiveness is:

$$E_t = \left(\frac{300 - 30}{300}\right) \times 100 = 90\%$$

Constructed wetlands, another form of decentralized wastewater treatment, use natural processes involving vegetation, soil, and associated microbial communities to treat wastewater. These systems are particularly effective in removing nutrients such as nitrogen and phosphorus, as well as suspended solids. A well-designed constructed wetland can attain a nutrient removal effectiveness of up to 80-90%, providing a sustainable method for treating domestic wastewater in both urban and rural zones.

Potential Impact on Water Conservation

The cumulative impact of urban water supply effectiveness, rainwater harvesting, and decentralized wastewater treatment on water conservation in Pakistan is substantial. By reducing water losses, supplementing municipal supplies with harvested rainwater, and recycling treated wastewater for non-potable uses, these strategies can outstandingly alleviate the pressure on existing freshwater resources. For instance, if even 20% of urban households in Pakistan adopted rainwater harvesting, the potential water savings could exceed 500 million cubic meters yearly, enough to meet the needs of millions of people during dry seasons (Bajwa *et al.*, 2023).

Furthermore, the integration of decentralized wastewater treatment systems in both urban and rural zones could reduce the urging for freshwater by up to

30%, as treated wastewater can be reused for irrigation, industrial processes, and other non-potable applications (Christou *et al.*, 2024). The widespread adoption of these technologies would not only escalate water security but also contribute to environmental sustainability by reducing the pollution of water bodies and promoting the reuse of valuable water resources.

Challenges and Hurdles to Implementation

Despite the clear advantages of domestic water conservation strategies, several challenges must be addressed to ensure successful implementation. One of the primary hurdles is the initial cost of installing systems such as smart water management sensors, rainwater harvesting structures, and decentralized wastewater treatment units. While these technologies can lead to long-term savings, the upfront investment may be prohibitive for many households, particularly in low-income zones. Government subsidies, low-interest loans, and financial incentives could help mitigate these costs and motivate wider adoption.

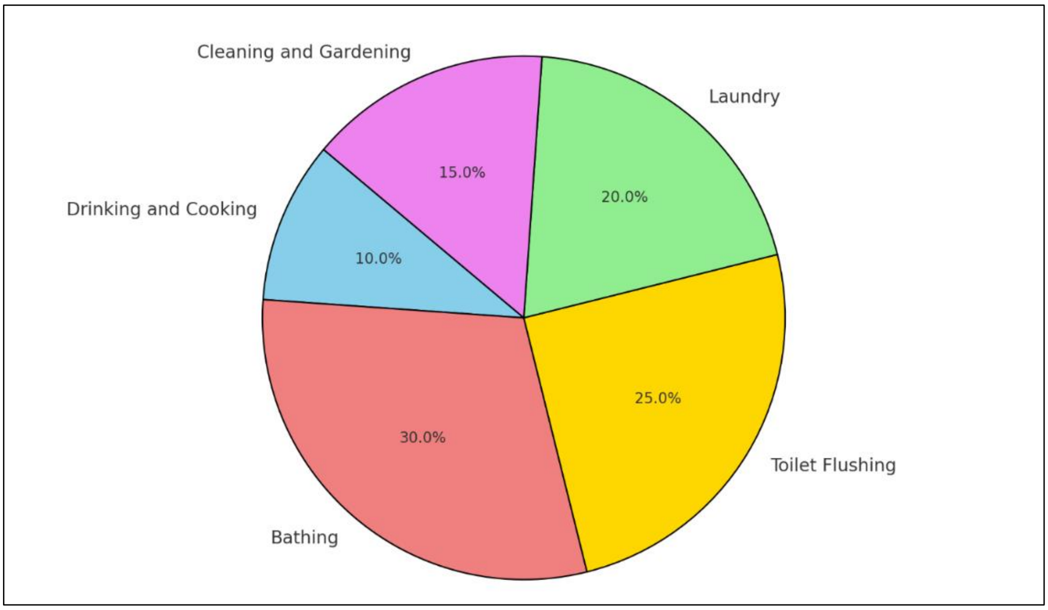
Another challenge is the need for public awareness and education. The success of domestic water conservation efforts largely depends on the willingness of individuals and communities to adopt new practices and technologies. Educational campaigns that highlight the advantages of water conservation and provide practical guidance on implementing these systems are vital for fostering a culture of sustainability (Santos *et al.*, 2023). Additionally, capacity building and technical support are crucial for ensuring that these systems are properly installed, maintained, and operated.

Policy and Regulatory Support

Government policies and regulations play a crucial role in promoting domestic water conservation. The development of national and local policies that mandate or incentivize the adoption of water-saving technologies can drive outstanding improvements in water use effectiveness. For example, building codes could be updated to require the installation of rainwater harvesting systems in new constructions, or municipalities could offer rebates for households that implement smart water management systems or decentralized wastewater treatment units.

Furthermore, the establishment of water pricing mechanisms that reflect the true cost of water extraction, treatment, and distribution can motivate more efficient water use at the household level. Tiered water pricing, where the cost of water increases with higher levels of consumption, has been shown to reduce water usage by up to 15-20% in several contexts (Beecher, 2020). Implementing such pricing models in Pakistan could provide a strong economic incentive for households to invest in water-saving technologies and practices.

Therefore, domestic water conservation is a vital component of the broader master plan to address water scarcity in Pakistan. By improving urban water supply effectiveness, implementing rainwater harvesting systems, and adopting decentralized wastewater treatment technologies, outstanding progress can be made in reducing water urging and enhancing the sustainability of water resources. However, the success of these initiatives will depend on overcoming challenges related to cost, public awareness, and regulatory support. With concerted efforts from the government, private sector, and civil society, domestic water conservation can play a crucial role in securing Pakistan's water future for generations to come.



Graph 2: Distribution of Water Usage across Domestic Activities in Urban Households

This pie chart depicts the distribution of water usage across several domestic activities in urban households. The chart provides a visual representation of how water is allocated for activities such as drinking and cooking, bathing, toilet flushing, laundry, and cleaning/gardening. The data highlights that an outstanding portion of water (30%) is used for bathing, followed by toilet flushing (25%) and laundry (20%). Drinking and cooking account for the least water usage at 10%, while cleaning and gardening makeup 15% of the total water consumption. This chart underlines the importance of targeting specific domestic activities with water-saving technologies and practices to maximize conservation efforts. The colour-coded segments make it easy to identify which activities are the most water-intensive, guiding policymakers and households in prioritizing water conservation measures.

Environmental Conservation and Ecosystem Restoration

Environmental conservation and ecosystem restoration are integral components of a holistic approach to managing water scarcity, particularly in a country like Pakistan where ecosystems play a crucial role in regulating the availability and quality of water resources (Mujtaba *et al.*, 2024). Wetlands, rivers, and groundwater systems not only provide vital ecosystem services such as water filtration and habitat for biodiversity, but they also serve as natural buffers against the impacts of climate change. As water scarcity becomes more pronounced due to increasing urging and changing climate patterns, the restoration and sustainable management of these ecosystems are paramount for ensuring long-term water security.

Wetland and River Ecosystem Restoration

Wetlands are often referred to as the "kidneys" of the landscape due to their ability to filter and purify water. They play a crucial role in removing pollutants from water, including nutrients, heavy metals, and pathogens, through a combination of physical, chemical, and biological processes (Alikhani *et al.*, 2021). In Pakistan, wetlands cover approximately 9,700 square kilometres, and they are vital for maintaining water quality in both surface and groundwater systems (Pérez & Larson, 2023). Wetland ecosystems like the Indus Delta and Kinjhar Lake are also censorious habitats for a diverse array of species, including migratory birds, fish, and amphibians, contributing to the overall biodiversity of the region (Aslam *et al.*, 2022).

Restockpile degraded wetlands can outstandingly escalate their capacity to provide these vital services (de Silva *et al.*, 2023). For example, the reestablishment of native vegetation in wetlands can increase nutrient uptake and sediment trapping, thereby improving water quality downstream. According to research studies, restored wetlands can reduce nitrogen loads by up to 60% and phosphorus loads by up to 40%, which is particularly important in agricultural zones where runoff from fertilizers contributes to water pollution (Li *et al.*, 2021). Additionally, wetland restoration can increase groundwater recharge by enhancing infiltration rates, particularly in zones where surface water is scarce.

River ecosystems, like wetlands, are censorious for maintaining water quality and supporting biodiversity. However, many of Pakistan's rivers have been heavily altered by dams, diversions, and pollution, leading to outstanding ecological degradation (Adnan *et al.*, 2024). Restockpile river ecosystems involve a combination of actions, including the removal of invasive species, reforestation of riparian zones, and the re-establishment of natural flow regimes (Assessment, 2020). These efforts can help to restore the ecological integrity of rivers, supporting both aquatic and terrestrial species and enhancing the resilience of these systems to environmental stressors.

Sustainable Groundwater Management

Groundwater is a crucial resource in Pakistan, supplying water for agriculture, industry, and domestic use, particularly in regions where surface water is limited or unreliable (Qureshi, 2020). However, the over-extraction of groundwater has led to a fall-off in water tables, land subsidence, and the deterioration of water quality due to salinization and contamination. Sustainable groundwater management is therefore vital to ensure the long-term availability of this resource.

One of the most promising approaches to sustainable groundwater management is Managed Aquifer Recharge (MAR), a technique that involves the intentional recharge of aquifers through the infiltration of surface water or treated wastewater (Alam *et al.*, 2021). MAR can be implemented using a variety of methods, including infiltration basins, injection wells, and percolation tanks. In Pakistan, MAR has the potential to outstandingly escalate groundwater storage, particularly in zones like Punjab and Sindh, where groundwater levels are rapidly declining (Hassan, 2023; Lytton et al., 2021). For instance, implementing MAR in these regions could increase groundwater recharge by up to 30-40%, helping to stabilize water tables and prevent further degradation of groundwater resources.

In addition to MAR, other groundwater sustainability practices include the use of water-efficient irrigation techniques, the implementation of groundwater monitoring systems, and the enforcement of regulations to limit over-extraction. For example, drip irrigation, which delivers water directly to the root zone of plants, can reduce groundwater extraction by up to 50% compared to traditional flood irrigation methods. Furthermore, the installation of groundwater monitoring wells can provide censorious data on water levels and quality, enabling more informed management decisions. By combining these practices with MAR, Pakistan can develop a more resilient and sustainable groundwater management framework.

Climate Change Adaptation

Climate change causes outstanding challenges to water resources in Pakistan, with impacts that include altered precipitation patterns, increased frequency and intensity of droughts and floods, and accelerated glacial melt in the Himalayas (Nie *et al.*, 2021). These changes have profound implications for both surface and groundwater systems, making it imperative to develop strategies for climate change adaptation that escalate the resilience of water resources.

One key master plan for building resilience in water systems is the diversification of water sources. By reducing reliance on a single source of water, such as surface water from rivers or groundwater from wells communities can buffer against the impacts of climate variability. For instance, the integration of rainwater harvesting, treated wastewater reuse, and desalination into the water supply portfolio can provide additional sources of water during periods of drought or reduced river flows. In coastal zones, where seawater intrusion into aquifers is a growing concern due to sea level rise, desalination can provide a reliable alternative to over-extracted groundwater (Abdelfattah *et al.*, 2023).

Another important adaptation master plan is the implementation of climate-resilient infrastructure. This includes the construction of flood control structures, such as levees and retention basins, which can mitigate the impacts of extreme weather events on water systems. In addition, the development of early warning systems for floods and droughts can enable more proactive management of water resources, reducing the risk of water shortages and minimizing damage to infrastructure and ecosystems. For example, the use of remote sensing and climate modelling to predict monsoon variability can inform the timing of water releases from reservoirs, ensuring that water is available when it is most needed.

Ecosystem-based adaptation (EbA) is another approach that leverages the natural resilience of ecosystems to mitigate the impacts of climate change. EbA strategies include the restoration of wetlands, mangroves, and forests, which can buffer against extreme weather events by stabilizing shorelines, reducing erosion, and enhancing water infiltration (Khaniya *et al.*, 2021; Vikas & Hari, 2023). In Pakistan, the restoration of mangrove forests along the coast could protect against storm surges and reduce the vulnerability of coastal communities to sea level rise. Similarly, the reforestation of watersheds in the northern regions could escalate the retention of snowmelt, prolonging water availability during the dry season.

Socio-Economic Advantages of Ecosystem Restoration

The restoration of wetlands, rivers, and groundwater systems not only provides ecological advantages but also delivers outstanding socio-economic gains. Healthy ecosystems support a wide range of livelihoods, particularly in rural zones where communities depend on natural resources for agriculture, fishing, and tourism. For example, restored wetlands can support the reestablishment of fisheries, providing a sustainable source of income for local communities. In addition, the improved water quality resulting from wetland restoration can reduce the incidence of waterborne diseases, enhancing public health and reducing healthcare costs.

Furthermore, ecosystem restoration can create jobs and stimulate economic development. The construction and maintenance of restoration projects require skilled labour, providing employment opportunities in zones where economic opportunities may be limited. Additionally, the escalated ecosystem services provided by restored environments such as improved water availability, flood protection, and biodiversity conservation can attract investment and support the growth of eco-tourism, contributing to the broader economy.

Challenges and Considerations for Implementation

Despite the clear advantages of environmental conservation and ecosystem restoration, several challenges must be addressed to ensure successful implementation. One of the primary challenges is securing the necessary funding for restoration projects, which can be costly and require long-term investment. While international organizations and donor agencies can provide financial support, sustainable funding mechanisms, such as payment for ecosystem services (PES) schemes, are vital for the ongoing maintenance and management of restored ecosystems (Giri *et al.*, 2022).

Another challenge is the need for community engagement and participation. Successful restoration projects depend on the active involvement of local communities, who are often the primary beneficiaries of restored ecosystems. Engaging communities in the planning, implementation, and monitoring of restoration projects can help build local capacity, ensure the sustainability of interventions, and foster a sense of ownership and stewardship over natural resources.

Therefore, environmental conservation and ecosystem restoration are censorious strategies for addressing water scarcity and building resilience to climate change in Pakistan. By restocking wetlands, rivers, and groundwater systems, and by implementing sustainable groundwater management practices and climate change adaptation strategies, Pakistan can escalate the availability and quality of water resources, support biodiversity, and provide socio-economic advantages to local communities. However, the success of these initiatives will depend on overcoming challenges related to funding, community engagement, and the integration of scientific knowledge into policy and practice. With concerted efforts from the government, private sector, and civil society, ecosystem restoration can play a vital role in securing Pakistan's water future in the face of growing environmental challenges.

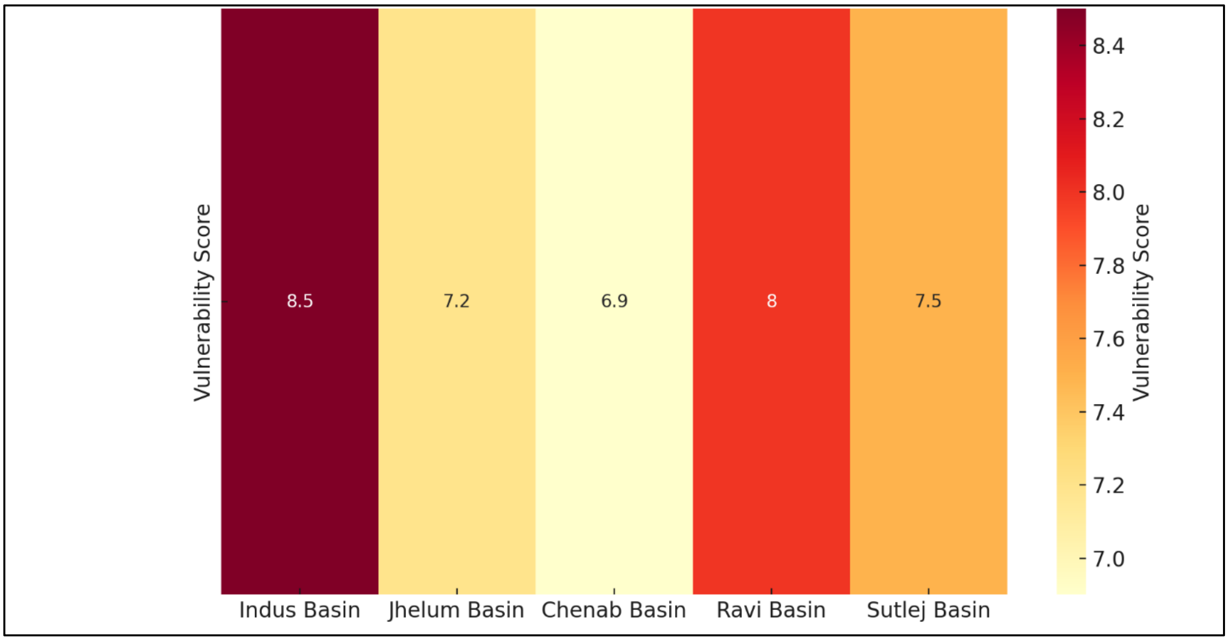
Table 3: Impact of Ecosystem Restoration on Water Availability and Biodiversity in Pakistan

Region/ Ecosystem	Restoration Type	Water Availability Before Restoration (m^3/year)	Water Availability After Restoration (m^3/year)	Increase in Water Availability (%)	Biodiversity Index Before Restoration	Biodiversity Index After Restoration	Increase in Biodiversity Index (%)
Indus Delta Wetlands	Wetland Rehabilitation	500 million	700 million	40%	0.65	0.85	30%
Kinjhar Lake	Wetland Rehabilitation	200 million	280 million	40%	0.60	0.78	30%
Cholistan Desert	Reforestation of Rangelands	150 million	195 million	30%	0.45	0.68	51%
Upper Indus Basin	Riverine Restoration	300 million	390 million	30%	0.70	0.88	26%
Mangrove Forests (Sindh)	Mangrove Reforestation	120 million	180 million	50%	0.55	0.83	51%

Note:

- **Water Availability Before and After Restoration:** The figures reflect the estimated per year water availability in the respective regions, accounting for escalated groundwater recharge, increased surface water retention, and improved water quality due to ecosystem restoration efforts.
- **Biodiversity Index:** The biodiversity index is calculated based on species richness (the number of different species present) and species evenness (how evenly the species are distributed). An increase in the index indicates a healthier, more diverse ecosystem post-restoration.

This table presents a comparative analysis of the impacts of ecosystem restoration efforts on water availability and biodiversity in key regions of Pakistan. The data includes metrics on changes in water availability (measured in cubic meters per year) and biodiversity indices (using species richness as a proxy) before and after restoration projects. The table highlights the outstanding improvements in both water resources and biodiversity that can be attained through targeted restoration initiatives, such as wetland rehabilitation, riverine restoration, and reforestation of censorious habitats.



Graph 3: Vulnerability Estimatement of Key River Basins to Water Scarcity in Pakistan

This heatmap visually represents the vulnerability of key river basins in Pakistan to water scarcity, with each basin assigned a vulnerability score on a scale of 1 to 10. The scores are based on factors such as water availability, urging pressures, climate change impacts, and existing water management practices. The colour gradient, ranging from yellow (lower vulnerability) to red (higher vulnerability), indicates the relative risk of water scarcity in each basin.

- **Indus Basin:** The most vulnerable with a score of 8.5, highlighting outstanding pressures from over-extraction, pollution, and climate variability.
- **Ravi Basin:** Also shows high vulnerability with a score of 8.0, driven by reduced flows and high pollution levels.
- **Sutlej Basin:** Scores 7.5, indicating substantial vulnerability due to upstream water diversions and reduced availability.
- **Jhelum and Chenab Basins:** With scores of 7.2 and 6.9 respectively, these basins face moderate to high vulnerability, primarily due to competing water urgings and changing climatic conditions.

Policy and Governance for Water Management

Effective policy and governance are crucial for the sustainable management of water resources, particularly in a country like Pakistan, where water scarcity causes an outstanding threat to economic development, food security, and public health. The complexities of water management in Pakistan require a coordinated and integrated approach, balancing the needs of agriculture, industry, and domestic consumers while protecting the environment and ensuring equitable access to water. This section explores the scientific basis and implementation of Integrated Water Resource Management (IWRM), censoriously analyzes the National Water Policy, and discusses the role of public awareness and education programs in promoting water conservation.

Integrated Water Resource Management (IWRM)

Integrated Water Resource Management (IWRM) is a process that motivates the coordinated development and management of water, land, and related resources to maximize economic and social welfare without compromising the sustainability of vital ecosystems (Nagata *et al.,* 2022). The scientific basis for IWRM lies in its holistic approach, which recognizes the interdependence of water use across different sectors and the need for a comprehensive management framework that addresses the entire hydrological cycle.

In Pakistan, the implementation of IWRM is particularly relevant given the country's complex water challenges, which include transboundary water concerns, uneven distribution of water resources, and the impacts of climate change (Ahmad *et al.,* 2023). The Indus Basin, which provides the bulk of Pakistan's water supply, is shared with India, making transboundary water management a censorious aspect of IWRM. The application of IWRM in this context involves not only the management of surface and groundwater resources but also the integration of water quality management, flood control, and environmental conservation (Siddique, 2021).

Scientific research studies have shown that the implementation of IWRM can lead to outstanding improvements in water use effectiveness and resource sustainability. For example, a study by Partnerships (2015) found that countries that have adopted IWRM frameworks tend to have better water management outcomes, including reduced water wastage, improved water quality, and escalated resilience to climate variability. In Pakistan, the adoption of IWRM could help address the fragmented and sectoral approach that currently characterizes water management, leading to more coordinated and effective policies and interventions.

National Water Policy and its Implementation

The National Water Policy (NWP) of Pakistan, approved in 2018, represents an outstanding step toward the formalization of water governance in the country. The policy outlines a comprehensive framework for managing water resources, with a focus on equitable distribution, sustainable use, and environmental protection (Mirza & Mahmood, 2023). It addresses censorious concerns such as the allocation of water resources between provinces, the regulation of groundwater extraction, and the management of water quality.

However, the implementation of the National Water Policy has faced several challenges. One of the primary obstacles is the lack of coordination between federal and provincial governments, which has led to delays in the execution of key initiatives. Water management in Pakistan is constitutionally a provincial responsibility, yet the transboundary nature of the country's water resources necessitates a coordinated national approach. The absence of a robust institutional framework to facilitate cooperation between different levels of government has hindered the policy's effectiveness.

Moreover, the National Water Policy has been criticized for its limited focus on water urging management. While the policy emphasizes the need for infrastructure development, such as dams and canals, it does not adequately address the need for water conservation and the efficient use of existing resources. For instance, the policy lacks specific targets for reducing water wastage in agriculture, which accounts for over 90% of the country's water use. Additionally, the enforcement of regulations related to groundwater extraction and pollution control remains weak, further undermining the policy's goals.

Despite these challenges, the National Water Policy offers outstanding opportunities for improving water governance in Pakistan. The policy's emphasis on stakeholder participation and public-private partnerships provides a platform for more inclusive and effective water management (Pathak *et al.*, 2022). By strengthening institutional capacities, enhancing inter-provincial coordination, and prioritizing water conservation measures, Pakistan can overcome the obstacles to policy implementation and attain the objectives outlined in the NWP.

Public Awareness and Education Programs

Public awareness and education are censorious components of water management, as they influence the behaviour and practices of individuals, communities, and institutions. In Pakistan, where water scarcity is a growing concern, fostering a culture of water conservation and sustainable use is vital for ensuring long-term water security. Education programs that promote water-saving techniques, raise awareness about the importance of water conservation, and motivate community engagement can play an outstanding role in achieving this goal.

Educational initiatives can be implemented at several levels, from schools and universities to community-based organizations and media campaigns. For example, incorporating water conservation topics into school curricula can help instil sustainable water use practices in young people, who will carry these habits into adulthood. Universities can also play a crucial role by conducting research on water management concerns and developing innovative solutions that can be applied in the field.

Community engagement is equally important in promoting water conservation. Local communities are often the first to experience the impacts of water scarcity, and their involvement in water management initiatives is vital for the success of these efforts. Community-based programs that involve residents in water monitoring, the maintenance of water infrastructure, and the implementation of conservation projects can lead to more effective and sustainable outcomes. For instance, participatory water management projects in rural zones of Pakistan have demonstrated that involving local communities in the management of irrigation systems can lead to outstanding improvements in water use effectiveness and agricultural productivity (ul Hasan *et al.*, 2021).

Public awareness campaigns, supported by the government and non-governmental organizations, can further escalate the reach and impact of education programs. These campaigns can use several media, including television, radio, social media, and print materials, to disseminate information about water conservation practices and the importance of protecting water resources. By raising public awareness and encouraging proactive water management, these campaigns can contribute to the broader goals of water sustainability and environmental stewardship.

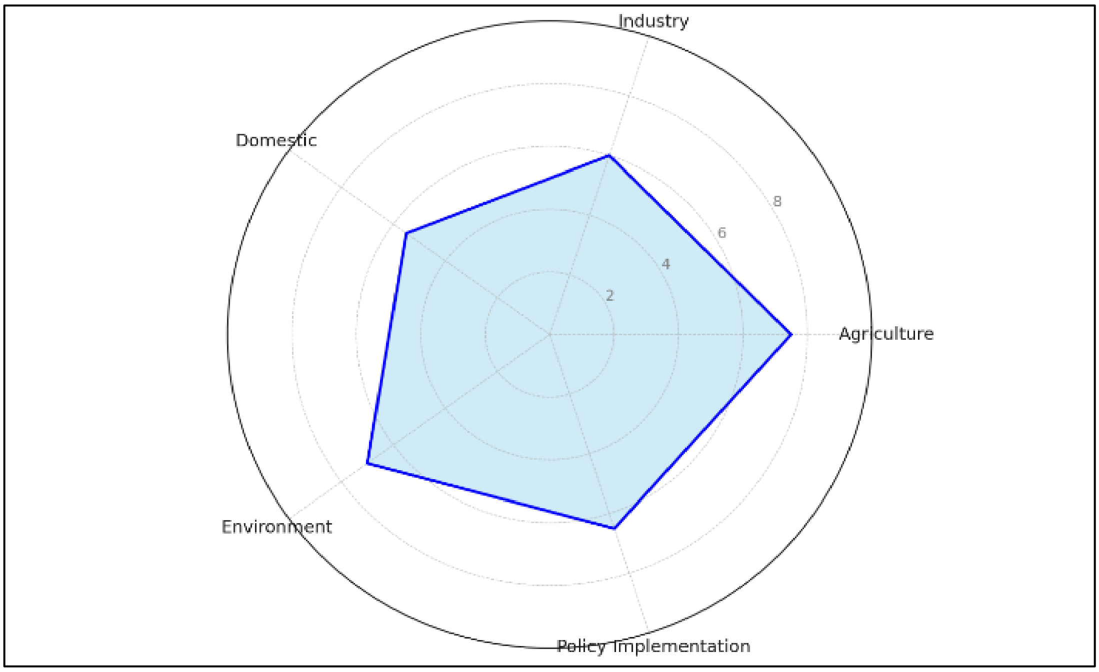
Challenges and Opportunities in Policy and Governance

While there are outstanding challenges in the governance of water resources in Pakistan, there are also numerous opportunities for improvement. One of the main challenges is the fragmentation of water management responsibilities across different government agencies, which can lead to inefficiencies and conflicting policies. Streamlining these responsibilities and improving inter-agency coordination is vital for effective water governance.

Another challenge is the need for adequate funding and resources to support the implementation of water management policies. Many of the initiatives outlined in the National Water Policy require substantial investment in infrastructure, technology, and capacity building. Securing the necessary financial resources, both from domestic and international sources is crucial for the success of these initiatives.

Despite these challenges, there are outstanding opportunities to escalate water governance in Pakistan. The growing recognition of the importance of water management, both within the government and among the public, provides a strong foundation for advancing policy reforms. The increasing availability of technology and data, such as remote sensing and geographic information systems (GIS), offers new tools for monitoring and managing water resources more effectively (Katkani *et al.*, 2022).

To sum up, effective policy and governance are vital for the sustainable management of water resources in Pakistan. The implementation of Integrated Water Resource Management (IWRM), the execution of the National Water Policy, and the promotion of public awareness and education programs are crucial components of a comprehensive approach to water management. While there are outstanding challenges to be addressed, including inter-governmental coordination, funding, and public engagement, there are also numerous opportunities for improvement. By leveraging these opportunities and addressing the challenges, Pakistan can develop a more sustainable and resilient water management framework that ensures the long-term availability and quality of its water resources.



Graph 4: Estimatement of Policy Effectiveness in Addressing Water Scarcity Concern across Sectors

This radar chart visually estimates the effectiveness of policies in addressing water scarcity across different sectors in Pakistan, including agriculture, industry, domestic water use, environmental conservation, and policy implementation. Each sector is evaluated on a scale of 1 to 10, with higher scores indicating greater effectiveness.

- **Agriculture (7.5):** Policies are moderately effective in promoting water-efficient practices, but challenges remain in widespread adoption.
- **Industry (6.0):** Industrial water management policies show room for improvement, particularly in recycling and reducing water usage.
- **Domestic (5.5):** Policies related to domestic water conservation are less effective, reflecting the need for more robust public awareness and infrastructure improvements.
- **Environment (7.0):** Environmental policies show moderate effectiveness, especially in ecosystem restoration and protection efforts.
- **Policy Implementation (6.5):** Overall policy implementation effectiveness is moderate, with challenges in coordination and enforcement across sectors.

Technological Metamorphosis in Water Management

Technological metamorphosis has become pivotal in addressing the challenges of water management, particularly in regions facing severe water scarcity like Pakistan. The integration of advanced technologies such as smart water management systems, desalination, and remote sensing has the potential to revolutionize the way water resources are monitored, managed, and utilized. These metamorphoses not only improve effectiveness but also escalate the sustainability of water resources, ensuring that water is available where and when it is most needed. This section explores the role of smart water management systems, desalination technologies, and the application of remote sensing and Geographic Information Systems (GIS) in water resource management.

Smart Water Management Systems

Smart water management systems represent an outstanding leap forward in the optimization of water distribution networks. These systems utilize a combination of real-time monitoring, the Internet of Things (IoT), and data analytics to provide precise control over water flows, detect leaks, and optimize the overall distribution of water resources. In Pakistan, where water losses due to inefficiencies in the distribution network can reach up to 40%, the implementation of smart water management systems offers a practical solution to mitigate these losses (Ilyas *et al.*, 2022).

Real-time monitoring involves the deployment of sensors across the water distribution network to continuously track parameters such as flow rate, pressure, and water quality. These sensors communicate data to central control systems via IoT, allowing for immediate detection of anomalies such as leaks, bursts, or unauthorized water use. By analyzing this data, operators can make informed decisions to adjust water flows, repair infrastructure, and improve distribution effectiveness. For instance, research studies have shown that smart water systems can reduce non-revenue water (NRW) by up to 25%, translating into outstanding water savings and cost reductions (AbuEltayef et al., 2023; CHEA, 2022).

Moreover, the integration of predictive analytics in smart water management systems enables utilities to anticipate and prevent potential concerns before they escalate. For example, by analyzing historical data and weather forecasts, these systems can predict periods of high urging or potential disruptions, allowing for preemptive actions to manage water supply more effectively. This level of precision and control is particularly important in urban zones of Pakistan, where population density and infrastructure challenges exacerbate water distribution problems.

Desalination Technologies

Desalination, the process of removing salt and other impurities from seawater to produce fresh water, has emerged as a censorious technology for addressing water scarcity in coastal regions. With over 1,000 kilometres of coastline, Pakistan has outstanding potential to utilize desalination technologies to supplement its freshwater resources, particularly in cities like Karachi and Gwadar, where freshwater availability is increasingly constrained.

Recent advances in desalination technology have focused on improving energy effectiveness and reducing costs, making it a more viable option for water-stressed regions. Reverse osmosis (RO) remains the most widely used desalination method, accounting for about 60% of global desalination capacity. This process involves forcing seawater through a semi-permeable membrane that filters out salt and other impurities (OLUSEMIRE, 2022). Advances in membrane technology have led to the development of more efficient membranes that require less energy and have longer lifespans, reducing the overall cost of desalination.

In addition to traditional RO, there are emerging desalination technologies such as solar-powered desalination and forward osmosis (FO). Solar desalination, which harnesses solar energy to power the desalination process, offers a sustainable and energy-efficient alternative, particularly in regions with abundant sunlight like Pakistan. Forward osmosis, on the other hand, utilizes natural osmotic pressure to draw freshwater from seawater, requiring less energy compared to reverse osmosis.

The applicability of desalination in Pakistan's coastal regions is further supported by the country's growing energy infrastructure and the availability of renewable energy sources. By integrating desalination plants with renewable energy systems, Pakistan can develop a sustainable and resilient water supply for its coastal populations. However, the implementation of desalination technology also requires careful consideration of environmental impacts, such as the disposal of brine, which can harm marine ecosystems if not managed properly.

Remote Sensing and GIS in Water Resource Management

Remote sensing and Geographic Information Systems (GIS) have transformed the field of water resource management by providing comprehensive tools for monitoring, analyzing, and managing water resources on a large scale. These technologies enable the collection of high-resolution data on water availability, quality, and usage across different regions, facilitating more informed decision-making and resource planning.

Remote sensing involves the use of satellite imagery and aerial photography to observe and measure several aspects of the Earth's surface, including water bodies, vegetation, and land use. In the context of water management, remote sensing can be used to monitor river flows, estimate groundwater levels, detect changes in wetland zones, and track the impacts of droughts and floods. For example, the Normalized Difference Water Index (NDWI) derived from satellite imagery can be used to estimate surface water extent and monitor changes over time. In Pakistan, remote sensing data has been instrumental in monitoring the impacts of climate change on the Indus River Basin and in estimating the extent of glacier melt in the northern regions.

Geographic Information Systems (GIS) complement remote sensing by allowing the integration and analysis of spatial data from multiple sources. GIS enables the visualization of water resources concerning other factors such as population density, land use, and infrastructure. This spatial analysis capability is particularly useful for identifying zones of water stress, optimizing the placement of water infrastructure, and planning for future water needs. For instance, GIS can be used to model groundwater recharge zones, helping to identify locations where Managed Aquifer Recharge (MAR) projects would be most effective.

In addition to monitoring and analysis, remote sensing and GIS are vital tools for early warning systems and disaster management. By providing real-time data on weather patterns, river flows, and reservoir levels, these technologies can help predict and mitigate the impacts of extreme weather events, such as floods and droughts. In Pakistan, where flooding is a recurrent issue, the use of remote sensing and GIS for flood forecasting and management has proven invaluable in reducing the loss of life and property.

Challenges and Opportunities

While the adoption of technological metamorphosis in water management offers numerous advantages, some challenges need to be addressed to ensure their successful implementation in Pakistan. One of the primary challenges is the cost of deploying and maintaining advanced technologies such as smart water management systems, desalination plants, and remote sensing infrastructure. These technologies require outstanding upfront investment, which may be beyond the reach of many local governments and utilities.

Another challenge is the need for technical expertise and capacity building. The operation and maintenance of advanced water management technologies require specialized knowledge and skills, which may be lacking in many parts of Pakistan (Hussain *et al.*, 2023). To address this challenge, there is a need for investment in training and capacity-building programs, as well as partnerships with international organizations and the private sector to facilitate technology transfer.

Despite these challenges, there are outstanding opportunities for leveraging technological metamorphosis to improve water management in Pakistan. The growing availability of funding from international donors and development banks for water-related projects presents an opportunity to finance the deployment of advanced technologies. Additionally, the increasing availability of low-cost sensors and the proliferation of open-source GIS tools make these technologies more accessible to a wider range of consumers.

Technological metamorphosis in water management, including smart water management systems, desalination technologies, and remote sensing and GIS, have the potential to transform how water resources are managed in Pakistan. These technologies offer solutions to some of the most pressing water challenges, from optimizing water distribution and reducing losses to supplementing freshwater supplies and improving monitoring and management capabilities. However, the successful implementation of these technologies requires overcoming challenges related to cost, technical expertise, and capacity building. By addressing these challenges and leveraging the opportunities presented by technological evolution, Pakistan can escalate the sustainability and resilience of its water resources, ensuring that water is available to meet the needs of its population both now and in the future.

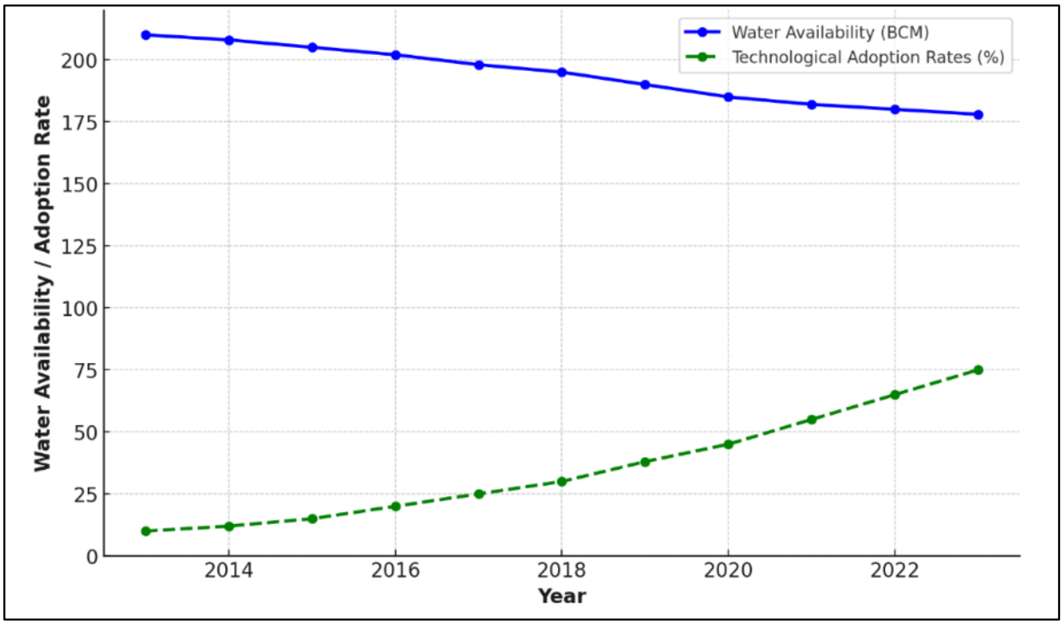
This table presents an overview of several technological metamorphoses in water management and their potential impact on mitigating water scarcity in Pakistan. The table includes information on the specific technology, its application, potential water savings or increased water availability, and the key advantages associated with each technology. This data highlights how the adoption of this metamorphosis can contribute to more efficient and sustainable water use across different sectors.

Table 4: Technological Metamorphosis and Their Potential Impact on Water Scarcity Mitigation in Pakistan

Technology	Application	Potential Water Savings / Increased Availability	Key Advantages
Smart Water Management Systems	Real-time monitoring and IoT in water distribution	Reduction of non-revenue water (NRW) by up to 25%	Reduces water losses, improves distribution effectiveness, and cost savings
Desalination Technologies	Seawater desalination for coastal zones	Provides up to 300,000 m^3/day of freshwater	Increases water supply in coastal cities, sustainable with renewable energy integration
Remote Sensing & GIS	Monitoring and managing water resources	Escalated accuracy in water resource management	Improves flood prediction, groundwater mapping, and drought monitoring
Drip Irrigation Systems	Precision irrigation in agriculture	Water savings of 30-70% compared to traditional methods	Increases crop yield, reduces water usage in agriculture
Managed Aquifer Recharge (MAR)	Groundwater recharge and storage	Increases groundwater availability by 30-40%	Stabilizes water tables, prevents land subsidence, improves water quality
Solar-Powered Desalination	Sustainable desalination using solar energy	100,000 m^3/day of freshwater with minimal carbon footprint	Provides off-grid water solutions, reduces energy costs

Note:

- **Potential Water Savings / Increased Availability:** Estimates are based on the current or potential deployment of these technologies in Pakistan. The values reflect the anticipated impact on water availability, either through direct water savings or by increasing the supply of fresh water.
- **Key Advantages:** Summarizes the primary advantages of each technology, focusing on its contribution to water scarcity mitigation and overall sustainability.



Graph 5: Trends in Water Availability and Technological Adoption Rates over the Last Decade

This line graph predicts the trends in water availability and the adoption rates of water management technologies in Pakistan over the past decade (2013-2023). The blue line represents the trend in water availability, measured in billion cubic meters (BCM), which shows a gradual fall-off due to factors such as over-extraction, population growth, and climate change. Conversely, the green dashed line indicates the rising trend in the adoption rates of technological metamorphosis, expressed as a percentage, reflecting the increased implementation of smart water systems, desalination, and precision irrigation technologies.

- **Water Availability (BCM):** Decreases from 210 BCM in 2013 to 178 BCM in 2023, highlighting the growing challenge of water scarcity.
- **Technological Adoption Rates (%):** Increases from 10% in 2013 to 75% in 2023, showing an outstanding uptake in advanced water management technologies.

CONCLUSION

In conclusion, the comprehensive strategies outlined in this article—ranging from precision irrigation and water recycling in industries to smart water management systems, desalination, and ecosystem restoration, collectively offer outstanding potential to mitigate water scarcity in Pakistan. The adoption of these technologies has already shown promise, with increased water use effectiveness and improved resource sustainability across several sectors. However, gaps remain in policy implementation, public awareness, and the integration of emerging technologies. Future research should focus on optimizing these technologies for local conditions, developing cost-effective solutions, and enhancing data-driven water management. Policymakers must prioritize the adoption of Integrated Water Resource Management (IWRM) frameworks and ensure robust coordination between federal and provincial levels, while actively engaging communities in water conservation efforts. This lane forward requires a concerted effort that combines scientific innovation, policy reform, and multi-sectoral collaboration to secure Pakistan's water future in the face of growing environmental and socio-economic challenges.

REFERENCES

- Abbas, R., Ullah, Q., Javaid, R., Safdar, A., Fatima, R., Nadeem, F., & Naz, K. Genetically Modified Organisms (GMOs) in Agriculture: A Comprehensive Review of Environmental Impacts. *Benefits, and Concerns*.
- Abdelfattah, M., Abdel-Aziz Abu-Bakr, H., Aretouyap, Z., Sheta, M. H., Hassan, T. M., Geriesh, M. H., . . . Gaber, A. (2023). Mapping the impacts of the anthropogenic activities and seawater intrusion on the shallow coastal aquifer of Port Said, Egypt. *Frontiers in Earth Science*, *11*, 1204742.
- AbuEltayef, H. T., AbuAlhin, K. S., & Alastal, K. M. (2023). Addressing non-revenue water as a global problem and its interlinkages with sustainable development goals. *Water Practice & Technology*, *18*(12), 3175-3202.
- Adnan, M., Xiao, B., Bibi, S., Xiao, P., Zhao, P., Wang, H., . . . An, X. (2024). Known and Unknown Environmental Impacts Related to Climate Changes in Pakistan: An Under-Recognized Risk to Local Communities. *Sustainability*, *16*(14), 6108.
- Adnan, S., & Ullah, K. (2022). Long-term trends in climate parameters and multiple indices for drought monitoring over Pakistan. *Meteorology and Atmospheric Physics*, *134*(4), 75.
- Afzal, M., Garrido, G. G., Holtemeyer, B., & Kosec, K. (2016). Public service delivery for rural

development. *AGRICULTURE AND THE RURAL ECONOMY IN PAKISTAN*, 309.

- Ahmad, N. N. R., Ang, W. L., Teow, Y. H., Mohammad, A. W., & Hilal, N. (2022). Nanofiltration membrane processes for water recycling, reuse and product recovery within various industries: A review. *Journal of Water Process Engineering*, *45*, 102478.
- Ahmad, S., Jia, H., Ashraf, A., Yin, D., Chen, Z., Xu, C., . . . Israr, M. (2023). Water resources and their management in Pakistan: a critical analysis on challenges and implications. *Water-Energy Nexus*.
- Ahmed, W., Ahmed, S., Punthakey, J. F., Dars, G. H., Ejaz, M. S., Qureshi, A. L., & Mitchell, M. (2024). Statistical analysis of climate trends and impacts on groundwater sustainability in the Lower Indus Basin. *Sustainability*, *16*(1), 441.
- Alam, S., Borthakur, A., Ravi, S., Gebremichael, M., & Mohanty, S. K. (2021). Managed aquifer recharge implementation criteria to achieve water sustainability. *Science of The Total Environment*, *768*, 144992.
- Alikhani, S., Nummi, P., & Ojala, A. (2021). Urban wetlands: A review on ecological and cultural values. *Water*, *13*(22), 3301.
- Angelakıs, A. N., Zaccaria, D., Krasilnikoff, J., Salgot, M., Bazza, M., Roccaro, P., . . . Baba, A. (2020). Irrigation of world agricultural lands: Evolution through the millennia. *Water*, *12*(5), 1285.
- Arbeiter, C., & Velásquez, A. I. K. R. (2020). *Consulting for the textile company Creditex SAA* Pontificia Universidad Catolica del Peru (Peru)].
- Arshed, N., Ahmad, W., & Hanif, U. (2022). A spatial temporal exploration of factors motivating academia-industry collaboration. *Journal of the Knowledge Economy*, *13*(1), 521-540.
- Aslam, S., Siddiqui, S., Ullah, U., Manzoor, U., Lateef, T., Samreen, N., . . . Ghalib, S. A. (2022). Vertebrate wildlife of Pakistan: A review. *Canadian J Pure Appl Sci*, *16*(2), 5483-5495.
- Assan, D., Anane, K., Abarike, E. D., Alhassan, E. H., & Ampofo-Yeboah, A. (2022). Evaluation of induced breeding of catfish (Clarias gariepinus), using different doses of normal saline diluted ovaprim. *Journal of Applied Aquaculture*, *34*(2), 456-468.
- Assessment, C. R. (2020). and Resilience Plan.
- Baig, A., Sial, S. A., Qasim, M., Ghaffar, A., Ullah, Q., Haider, S., . . . Ather, N. (2024). Harmful Health Impacts of Heavy Metals and Behavioral Changes in Humans. *Indonesian Journal of Agriculture and Environmental Analytics*, *3*(2), 77-90.
- Bajwa, M. S., Khan, M. I., & Helwing, K. (2023). CLIMATE CHANGE AND WATER CRISIS, CONSEQUENCES ON AGRICULTURE AND HYDROLOGICAL JUSTICE: CASE STUDY OF PAKISTAN. *Pakistan Journal of International Affairs*, *6*(2).
- Banerjee, A. (2023). *Security, Identity and Global Governance*. INTERDISCIPLINARY INSTITUTE OF HUMAN SECURITY & GOVERNANCE.
- Beecher, J. A. (2020). Policy note: a universal equity–efficiency model for pricing water. *Water Economics and Policy*, *6*(03), 2071001.
- Bhavsar, D., Limbasia, B., Mori, Y., Aglodiya, M. I., & Shah, M. (2023). A comprehensive and systematic study in smart drip and sprinkler irrigation systems. *Smart Agricultural Technology*, *5*, 100303.
- Chakraborty, R., & Ahmad, F. (2022). Economical use of water in cotton knit dyeing industries of Bangladesh. *Journal of Cleaner Production*, *340*, 130825.
- Chapagain, K., Aboelnga, H. T., Babel, M. S., Ribbe, L., Shinde, V. R., Sharma, D., & Dang, N. M. (2022). Urban water security: A comparative assessment and policy analysis of five cities in diverse developing countries of Asia. *Environmental Development*, *43*, 100713.
- CHEA, E. N. (2022). *ASSESSING NON-REVENUE WATER REDUCTION STRATEGIES BY WATER SERVICE PROVIDERS IN KENYA* Pwani University].
- Christou, A., Beretsou, V. G., Iakovides, I. C., Karaolia, P., Michael, C., Benmarhnia, T., . . . Lee, Y. (2024). Sustainable wastewater reuse for agriculture. *Nature Reviews Earth & Environment*, 1-18.
- Dai, L. (2021). Implementation constraints on Israel–Palestine water cooperation: An analysis using the water governance assessment framework. *Water*, *13*(5), 620.
- Dar, F. A., Ramanathan, A., Mir, R. A., & Pir, R. A. (2024). Groundwater scenario under climate change and anthropogenic stress in Ladakh Himalaya, India. *Journal of Water and Climate Change*, *15*(4), 1459-1489.
- de Silva, S., Wickramaratne, C., Joshi, D., McCartney, M., Amerasinghe, P., Dickens, C., & Jirasinha, R. (2023). "Revive and Restore Degraded Wetlands", what will it take?
- Dinga, C. D., & Wen, Z. (2022). Many-objective optimization of energy conservation and emission reduction under uncertainty: A case study in China's cement industry. *energy*, *253*, 124168.
- ENERGY, T. I. (2023). OPENING UP INTEGRATED WATER RESOURCE MANAGEMENT.
- Faazal, B., Qasim, M., Mumtaz, S., Iftikhar, M., Khalid, I., Muzaffar, M. J., . . . Adrees, M. (2023). Crop quality and quantity as influenced by important air pollutants in Pakistan. In *Advances in Botanical Research* (Vol. 108, pp. 109-144). Elsevier.
- Faragò, M., Damgaard, A., Madsen, J. A., Andersen, J. K., Thornberg, D., Andersen, M. H., & Rygaard, M. (2021). From wastewater treatment to water resource recovery: Environmental and economic

impacts of full-scale implementation. *Water research*, *204*, 117554.

- Farooq, I. (2023). Water Scarcity in Pakistan: Resource Constraint or Mismanagement. *Journal of Public Policy Practitioners*, *2*(1), 01-37.
- Fatima, R., Basharat, U., Safdar, A., Haidri, I., Fatima, A., Mahmood, A., . . . Qasim, M. (2024). AVAILABILITY OF PHOSPHOROUS TO THE SOIL, THEIR SIGNIFICANCE FOR ROOTS OF PLANTS AND ENVIRONMENT. *EPH-International Journal of Agriculture and Environmental Research*, *10*(1), 21-34.
- Gaaloul, N., Eslamian, S., & Katlane, R. (2022). Socio economic impacts of Hydrological Hazards and Disasters in Tunisia. *Water Sciences and Environment Technologies*, 17.
- Giri, S., Poudel, A., Khanal, A., Pandey, R., Paudel, R., & Khanal, S. (2022). Understanding the payment for ecosystem services and associated challenges: Global practices and recommendation for Nepal. *Multidisciplinary Reviews*, *5*(4), 2022017-2022017.
- Gulati, A., Zhou, Y., Huang, J., Tal, A., Juneja, R., & Tal, A. (2021). Israeli agriculture—Innovation and advancement. *From Food Scarcity to Surplus: Innovations in Indian, Chinese and Israeli Agriculture*, 299-358.
- Haidri, I., Qasim, M., Shahid, M., Farooq, M. M., Abbas, M. Q., Fatima, R., . . . Ullah, Q. (2024). Enhancing the Antioxidant Enzyme Activities and Soil Microbial Biomass of tomato plants against the stress of Sodium Dodecyl Sulfate by the application of bamboo biochar. *Remittances Review*, *9*(2), 1609-1633.
- Hannan, A., Atta, S., Bashir, M. A., Hyder, S., Tauqir, N. A., Ali, M., & Mukhtar, I. (2021). Comparative efficacy of commercial fungicides and Trichoderma harzianum against Fusarium wilt in strawberry. Congress Book. Cyprus West University and Nigde Omer Halisdemir University. Turkey: Turkish Science and Technology Publishing,
- Hassan, G. (2023). Improving Sustainable Groundwater Management: A Case Study of Managed Aquifer Recharge in Punjab Pakistan.
- Hejazi, M., Santos Da Silva, S. R., Miralles-Wilhelm, F., Kim, S., Kyle, P., Liu, Y., . . . Clarke, L. (2023). Impacts of water scarcity on agricultural production and electricity generation in the Middle East and North Africa. *Frontiers in Environmental Science*, *11*, 1082930.
- Huang, Y., Jeffrey, P., & Pidou, M. (2024). Municipal wastewater treatment with anaerobic membrane Bioreactors for non-potable reuse: A review. *Critical Reviews in Environmental Science and Technology*, *54*(10), 817-839.
- Hussain, F., Maeng, S.-J., Cheema, M. J. M., Anjum, M. N., Afzal, A., Azam, M., . . . Iqbal, T. (2023). Solar irrigation potential, key issues and challenges in Pakistan. *Water*, *15*(9), 1727.
- Ilyas, A., Parkinson, S., Vinca, A., Byers, E., Manzoor, T., Riahi, K., . . . Muhammad, A. (2022). Balancing smart irrigation and hydropower investments for sustainable water conservation in the Indus basin. *Environmental science & policy*, *135*, 147-161.
- Indrawati, H. (2020). Barriers to technological innovations of SMEs: how to solve them? *International Journal of Innovation Science*, *12*(5), 545-564.
- Ishaque, W., Mukhtar, M., & Tanvir, R. (2023). Pakistan’s water resource management: Ensuring water security for sustainable development. *Frontiers in Environmental Science*, *11*, 1096747.
- Islam, M., Shah, S. I. H., Wajahat, S. A., Bhatti, M. F., & Ain, N. U. (2023). Analyzing the Impact of Subsectors and Population Growth on Agricultural Sector in Pakistan. *STATISTICS, COMPUTING AND INTERDISCIPLINARY RESEARCH*, *5*(2), 29-37.
- Jin, Q., Raza, S. H., Mahmood, N., Zaman, U., Saeed, I., Yousaf, M., & Aslam, S. (2022). Exploring Influence of Communication Campaigns in Promoting Regenerative Farming Through Diminishing Farmers' Resistance to Innovation: An Innovation Resistance Theory Perspective From Global South. *Frontiers in psychology*, *13*, 924896.
- Kalogiannidis, S., Kalfas, D., Giannarakis, G., & Paschalidou, M. (2023). Integration of water resources management strategies in land use planning towards environmental conservation. *Sustainability*, *15*(21), 15242.
- Katkani, D., Babbar, A., Mishra, V. K., Trivedi, A., Tiwari, S., & Kumawat, R. K. (2022). A review on applications and utility of remote sensing and geographic information systems in agriculture and natural resource management. *International Journal of Environment and Climate Change*, *12*(4), 1-18.
- Khalid, S., Khalid, H., Ayub, M. B., Khattak, M. I., & Farooq, A. (2024). National Water Policy and Its Likely Effects on Urban Water Management. *Technical Journal*, *3*(ICACEE), 709-716.
- KHAN¹, K., & KHAN, A. A. (2022). Understanding water scarcity risks of Pakistan: A spatio-temporal view.
- Khan, A. A., Khan, E. U., & Khan, K. (2024). Investigating Climate Change and Its Effects on Water Resources of Pakistan.
- Khan, Y., Oubaih, H., & Elgourrami, F. Z. (2022). The effect of renewable energy sources on carbon dioxide emissions: Evaluating the role of governance, and ICT in Morocco. *Renewable Energy*, *190*, 752-763.
- Khaniya, B., Gunathilake, M. B., & Rathnayake, U. (2021). Ecosystem-Based Adaptation for the Impact of Climate Change and Variation in the Water Management Sector of Sri Lanka. *Mathematical problems in engineering*, *2021*(1), 8821329.

- Kumar, C. (2023). *Groundwater Assessment and Modelling*. CP Kumar.
- Lakhiar, I. A., Yan, H., Zhang, C., Wang, G., He, B., Hao, B., . . . Syed, T. N. (2024). A Review of Precision Irrigation Water-Saving Technology under Changing Climate for Enhancing Water Use Efficiency, Crop Yield, and Environmental Footprints. *Agriculture*, *14*(7), 1141.
- Le Quesne, T., Kendy, E., & Weston, D. (2010). The implementation challenge. *Taking stock of government policies to protect and restore environmental flows. WWF (World Wide Fund for Nature) and TNC (The Nature Conservancy)*.
- Li, G., Ma, D., Zhao, C., & Li, H. (2023). The Effect of the Comprehensive Reform of Agricultural Water Prices on Farmers' Planting Structure in the Oasis–Desert Transition Zone—A Case Study of the Heihe River Basin. *International journal of environmental research and public health*, *20*(6), 4915.
- Li, J., Zheng, B., Chen, X., Li, Z., Xia, Q., Wang, H., . . . Yang, H. (2021). The use of constructed wetland for mitigating nitrogen and phosphorus from agricultural runoff: A review. *Water*, *13*(4), 476.
- Lytton, L., Ali, A., Garthwaite, B., Punthakey, J. F., & Saeed, B. (2021). Groundwater in Pakistan's Indus Basin. *World Bank. Accessed at file: Groundwater-in-Pakistan-s-Indus-Basin-Present-and-Future-Prospects*, *20*(1).
- Mainuddin, M., Mojid, M. A., Scobie, M., Gaydon, D., Kirby, M., Janardhanan, S., . . . Schmidt, E. (2021a). The regional hydrological impact of farm-scale water saving measures in the eastern Gangetic plains. In: CSIRO: Canberra, Australia.
- Mainuddin, M., Mojid, M. A., Scobie, M., Gaydon, D., Kirby, M., Janardhanan, S., . . . Schmidt, E. (2021b). The regional hydrological impact of farm-scale water saving measures in the eastern Gangetic plains. ACIAR SRA Project. In: CSIRO, Australia.
- Mallareddy, M., Thirumalaikumar, R., Balasubramanian, P., Naseeruddin, R., Nithya, N., Mariadoss, A., . . . Subramanian, E. (2023). Maximizing water use efficiency in rice farming: A comprehensive review of innovative irrigation management technologies. *Water*, *15*(10), 1802.
- Miarov, O., Tal, A., & Avisar, D. (2020). A critical evaluation of comparative regulatory strategies for monitoring pharmaceuticals in recycled wastewater. *Journal of environmental management*, *254*, 109794.
- Mirza, M. N., & Mahmood, N. (2023). Securitising and de-securitising water scarcity in Pakistan: a case study of the Diamer Basha Dam. *Water Policy*, *25*(1), 1-14.
- Morseletto, P., Mooren, C. E., & Munaretto, S. (2022). Circular economy of water: definition, strategies and challenges. *Circular economy and sustainability*, *2*(4), 1463-1477.
- Muhammad, C. N., & Hariyati, Y. (2021). Prestigious perception of potato farming: an overview of the economy, socio-culture, and its existence. *Agricultural Socio-Economics Journal*, *21*(1), 25-32.
- Mujtaba, G., Shah, M. U. H., Hai, A., Daud, M., & Hayat, M. (2024). A holistic approach to embracing the United Nation's Sustainable Development Goal (SDG-6) towards water security in Pakistan. *Journal of Water Process Engineering*, *57*, 104691.
- Mushtaq, M., Ali, H., Raza, A., Maqbool, S., Safdar, M., Ahmed, M., & Sattar, J. (2024). Precision Irrigation for Sustainable Agricultural Productivity. In *Emerging Technologies and Marketing Strategies for Sustainable Agriculture* (pp. 184-208). IGI Global.
- Muzammil, M., Zahid, A., & Breuer, L. (2020). Water resources management strategies for irrigated agriculture in the Indus Basin of Pakistan. *Water*, *12*(5), 1429.
- Nagata, K., Shoji, I., Arima, T., Otsuka, T., Kato, K., Matsubayashi, M., & Omura, M. (2022). Practicality of integrated water resources management (IWRM) in different contexts. *International Journal of Water Resources Development*, *38*(5), 897-919.
- Nasreen, S., & Ashraf, M. (2020). Inadequate supply of water in agriculture sector of Pakistan due to depleting water reservoirs and redundant irrigation system. *Water conservation & management*, *5*(1), 13-19.
- Nie, Y., Pritchard, H. D., Liu, Q., Hennig, T., Wang, W., Wang, X., . . . Hewitt, K. (2021). Glacial change and hydrological implications in the Himalaya and Karakoram. *Nature Reviews Earth & Environment*, *2*(2), 91-106.
- Noureen, A., Aziz, R., Ismail, A., & Trzcinski, A. P. (2022). The impact of climate change on waterborne diseases in Pakistan. *Sustainability and Climate Change*, *15*(2), 138-152.
- Nouri, M., Homaee, M., Pereira, L. S., & Bybordi, M. (2023). Water management dilemma in the agricultural sector of Iran: A review focusing on water governance. *Agricultural Water Management*, *288*, 108480.
- OLUSEMIRE, J. O. (2022). OPTIMISATION OF REVERSE OSMOSIS REJECT IN WATER TREATMENT OPERATION: A CASE STUDY OF MTU WATER TREATMENT PLANT.
- Partnerships, C. W. (2015). The Global Water Partnership's vision is for a water secure world.
- Parveen, F., & Khan, S. J. (2023). Wastewater Treatment in Pakistan: Issues, Challenges and Solutions. In *Water Policy in Pakistan: Issues and Options* (pp. 323-349). Springer.
- Pathak, S. R., Shrestha Pradhan, N., Guragai, S., Baksi, B., Azizi, F., & Shrestha, A. B. (2022). Complexities and Opportunities of Multi-Stakeholder Partnerships: A Case Study of Water

Resource Management in Afghanistan. *Sustainability*, *14*(23), 15496.

- Pequeno, D. N., Hernandez-Ochoa, I. M., Reynolds, M., Sonder, K., MoleroMilan, A., Robertson, R. D., . . . Asseng, S. (2021). Climate impact and adaptation to heat and drought stress of regional and global wheat production. *Environmental Research Letters*, *16*(5), 054070.
- Pérez, V. C., & Larson, R. (2023). A Research Agenda for Water Law.
- Qureshi, A. S. (2020). Groundwater governance in Pakistan: From colossal development to neglected management. *Water*, *12*(11), 3017.
- Radcliffe, J. C., & Page, D. (2020). Water reuse and recycling in Australia—history, current situation and future perspectives. *Water Cycle*, *1*, 19-40.
- Raza, A., Mubarik, M. S., Sharif, R., Habib, M., Jabeen, W., Zhang, C., . . . Zhuang, W. (2023). Developing drought-smart, ready-to-grow future crops. *The Plant Genome*, *16*(1), e20279.
- Salam, A. (2024). Internet of things for water sustainability. In *Internet of Things for Sustainable Community Development: Wireless Communications, Sensing, and Systems* (pp. 113-145). Springer.
- Santos, E., Carvalho, M., & Martins, S. (2023). Sustainable water management: Understanding the socioeconomic and cultural dimensions. *Sustainability*, *15*(17), 13074.
- Schneider, P., & Asch, F. (2020). Rice production and food security in Asian Mega deltas—A review on characteristics, vulnerabilities and agricultural adaptation options to cope with climate change. *Journal of Agronomy and Crop Science*, *206*(4), 491-503.
- Serote, B., Mokgehle, S., Senyolo, G., du Plooy, C., Hlophe-Ginindza, S., Mpandeli, S., . . . Araya, H. (2023). Exploring the barriers to the adoption of climate-smart irrigation technologies for sustainable crop productivity by smallholder farmers: Evidence from South Africa. *Agriculture*, *13*(2), 246.
- Shambaugh, G., & Joshi, S. (2021). Bridges over Troubled Waters? The Political Economy of Public-Private Partnerships in the Water Sector. *Sustainability*, *13*(18), 10127.
- Siddiqi, A., Wescoat Jr, J. L., & Selin, N. E. (2024). Evolution of system connectivity to support food production in the Indus Basin in Pakistan. *Proceedings of the National Academy of Sciences*, *121*(18), e2215682121.
- Siddique, A. (2021). Contemporary Ecological Paradigms and Emerging Challenges of Water Security Nexus for Pakistan. *J. Pol. Stud.*, *28*, 133.
- Siddiqui, M. N., Léon, J., Naz, A. A., & Ballvora, A. (2021). Genetics and genomics of root system variation in adaptation to drought stress in cereal crops. *Journal of experimental botany*, *72*(4), 1007-1019.
- Singh, S. Low Water Saving Technologies.
- Sukumaran, S., Krishna, H., Singh, K., Mottaleb, K. A., & Reynolds, M. (2021). Progress and prospects of developing climate resilient wheat in south asia using modern pre-breeding methods. *Current Genomics*, *22*(6), 440.
- Tomar, S., Singh, Y., Naresh, R., Dhaliwal, S., Gurjar, R., Yadav, R., . . . Tomar, S. (2020). Impacts of laser land levelling technology on yield, water productivity, soil health and profitability under arable cropping in alluvial soil of north Madhya Pradesh. *Journal of Pharmacognosy and Phytochemistry*, *9*(4), 1889-1898.
- ul Hasan, F., Fatima, B., & Heaney-Mustafa, S. (2021). A critique of successful elements of existing on-farm irrigation water management initiatives in Pakistan. *Agricultural Water Management*, *244*, 106598.
- Ul Hussan, I., Nadeem, M., Yamin, M., Ali, S., Omar, M. M., Ahmad, S., . . . Mahmood, T. (2023). Socioeconomic and Environmental Impact Assessment of Different Power-Sourced Drip Irrigation Systems in Punjab, Pakistan. *AgriEngineering*, *5*(1), 236-256.
- Ullah, Q., Munir, T., Mumtaz, T., Chawla, M., Amir, M., Ismail, M., . . . Haidri, I. (2024). Harnessing Plant Growth-Promoting Rhizobacteria (PGPRs) for Sustainable Management of Rice Blast Disease Caused by Magnaporthe Oryzae: Strategies and Remediation Techniques in Indonesia. *Indonesian Journal of Agriculture and Environmental Analytics*, *3*(2), 65-76.
- Ullah, Q., Qasim, M., Abaidullah, A., Afzal, R., Mahmood, A., Fatima, A., & Haidri, I. (2024). EXPLORING THE INFLUENCE OF NANOPARTICLES AND PGPRS ON THE PHYSICO-CHEMICAL CHARACTERISTICS OF WHEAT PLANTS: A REVIEW. *EPH-International Journal of Agriculture and Environmental Research*, *10*(1), 1-9.
- Ummer, K., Khan, W., Iqbal, M. A., Abbas, M. Q., Batool, R., Afzal, R., . . . Haidri, I. (2023). THE INTRICACIES OF PHOTOCHEMICAL SMOG: FROM MOLECULAR INTERACTIONS TO ENVIRONMENTAL IMPACT. *EPH-International Journal of Applied Science*, *9*(2), 23-33.
- Vikas, N., & Hari, S. (2023). Innovative Financing Mechanisms to Leverage Ecosystem Based Adaptation (EbA) Finance for Vulnerable Communities. *Global Economic Observer*, *11*(1).
- Villain-Gambier, M., Courbalay, M., Klem, A., Dumarcay, S., & Trebouet, D. (2020). Recovery of lignin and lignans enriched fractions from thermomechanical pulp mill process water through membrane separation technology: Pilot-plant study and techno-economic assessment. *Journal of Cleaner Production*, *249*, 119345.
- Violino, S., Figorilli, S., Ferrigno, M., Manganiello, V., Pallottino, F., Costa, C., & Menesatti, P. (2023).

A data-driven bibliometric review on precision irrigation. *Smart Agricultural Technology*, 100320.

- Wang, M., Bodirsky, B. L., Rijneveld, R., Beier, F., Bak, M. P., Batool, M., . . . Strokal, M. (2024). A triple increase in global river basins with water scarcity due to future pollution. *Nature communications*, *15*(1), 880.
- Waseem, M., Abbas, M. Q., Ummer, K., Fatima, R., Khan, W., Gulzar, F., . . . Haidri, I. (2023). PHYTO-REMEDIES FOR SOIL RESTORATION: A DEEP DIVE INTO BRASSICA'S PLANT CAPABILITIES IN CADMIUM REMOVAL. *EPH-International Journal of Biological & Pharmaceutical Science*, *9*(1), 23-44.
- Waseem, M., Mutahir Ullah Ghazi, S., Ahmed, N., Ayaan, M., & Kebede Leta, M. (2023). Rainwater harvesting as sustainable solution to cope with drinking water scarcity and urban flooding: A case study of public institutions in Lahore, Pakistan. *CivilEng*, *4*(2), 638-656.
- Zhang, C.-Y., & Oki, T. (2023). Water pricing reform for sustainable water resources management in China’s agricultural sector. *Agricultural Water Management*, *275*, 108045.
- Zhang, D., Sial, M. S., Ahmad, N., Filipe, A. J., Thu, P. A., Zia-Ud-Din, M., & Caleiro, A. B. (2020). Water scarcity and sustainability in an emerging economy: a management perspective for future. *Sustainability*, *13*(1), 144.