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Strategies for Enhancing Water Security in Iran's Agricultural Sector under Climate Change

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ABSTRACT

The issue of climate change and its associated water security challenges has become a growing concern for Iran, particularly in its agricultural sector. Increasing population, rising demand for agricultural products, and the need for food security exacerbate these challenges. This study highlights the risks posed by reduced precipitation, rising temperatures, and inefficient water management practices, including heavy reliance on groundwater and outdated irrigation systems. It emphasizes the urgent need for modern irrigation technologies, such as water recycling (NEWater), and robust governance reforms to improve water use efficiency, analyzed through the HES framework. The study concludes that adopting a comprehensive, long-term strategy, incorporating technological innovations, localized water management practices, and enhanced governance can mitigate the impacts of climate change and ensure the sustainable use of water resources in Iran's agricultural sector.

Keywords: Agriculture, Climate change, HES analysis, Iran, NEWater, Water security.

INTRODUCTION

It is undeniable that climate change and water security are fundamental global challenges for sustainable development and human security. Water is essential for life and is a crucial aspect of the goals and challenges of sustainable development. Moreover, climate change can exacerbate water tensions and lead to a scarcity crisis, provoking both positive and negative shifts globally (Zhou *et al*., 2021). Scholars, including Patrick (2022), have documented the impact of these twin challenges on human security and development. In Iran, these challenges are further intensified by multiple vulnerabilities, such as population growth, poverty, governance deficiencies, and the effects of economic sanctions (Farzanegan and Habibpour, 2017; Pourezzat *et al*., 2018; Shahriyari *et al*., 2018; Abdoli, 2020). Similarly, Biswas and Tortajada's (2022) study on the estimated economic losses caused by climate-related disasters shows that economic losses as a percentage of GDP are significantly higher for low-income countries compared to high-income. This disparity may exacerbate inequality both between rich and poor nations and within low- and middle-income countries (Biswas and Tortajada, 2022). Reports from Iran indicate that a 1% increase in the temperature across the country's provinces could lead to a 0.12% decrease in GDP growth, contributing to a climate-induced reduction in Iran's overall economic growth (Salehi Komroudi and Abounoori, 2019).

The escalating population growth in Iran presents significant challenges, particularly in meeting the increasing demand for essential resources such as food, water, and energy. With the population projected to reach 200 million by 2050, the strain on existing resources will intensify, further complicating efforts to tackle climate

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change. As the population grows, pressure on agricultural systems to produce more food increases, leading to higher water consumption and energy use. In the context of climate change, this demand becomes even more critical, as rising temperatures and decreasing precipitation threaten the availability of these vital resources. Moreover, the relationship between climate and agriculture is inherently bidirectional. Human activities, particularly intensive agricultural practices, contribute to greenhouse gas emissions, accelerating climate change. In turn, these climatic shifts exacerbate agricultural vulnerabilities by increasing water requirements, reducing crop yields, and diminishing overall productivity. This reciprocal relationship highlights the need for sustainable solutions that address both climate change mitigation and adaptation in the agricultural sector.

The growing emphasis on sustainable pathways toward improving water security led Grey and Sadoff (2007) to define water security as "the availability of an acceptable quantity and quality of water that is essential to health, livelihoods, ecosystems, and production, and at the same time the extent of the risks that water poses to people, the environment, and the economy". This definition underscores that water is not only vital for human survival but also serves as the economic foundation for millions of enterprises, farms, power plants, and industries, all of which rely on dependable water quality and availability (Gunda *et al*., 2019).

In this regard, some researchers argue that the scope of social challenges in achieving and maintaining sustainable water security is influenced by several factors, including the followings (Grey and Sadoff, 2007):

1. The hydrological environment, which is a natural heritage;
2. The socio-economic environment, reflecting the economic structure and behavior of its actors, as well as the natural, cultural, and political heritage;
3. Future environmental changes, notably climate change.

Consequently, addressing water security concerns requires not only policymaking, comprehensive planning, technological innovations, and sectoral collaboration but also consideration of their profound impacts on both natural and social environments. Even if complete water security cannot be fully achieved, policy instruments should be expanded to enhance water security. These tools may include governance strategies, institutional reforms, market-based approaches, adaptive capacity-building, and information exchange (World Bank, 2015; OECD, 2013; United Nations University, 2013).

Given the interconnectedness of these vulnerabilities and the dynamic nature of the challenges Iran faces, managing these concerns becomes increasingly complex. By consuming natural resources, we generate more greenhouse gases, which contribute to global warming and further climate change through various pathways. These issues increase the range of secondary problems that can seriously affect food production, energy needs, usage patterns, and water management.

This has often been a recurring issue, where solutions to one problem can create significant challenges in other areas. As such, it is essential to ensure that solutions deemed effective for addressing one major problem do not create issues in other contexts. Instead of focusing solely on isolated problems, it is crucial to develop solutions that consider and evaluate the interconnected challenges.

This research fills a significant gap in the literature by exploring the interplay between climate change and water security in Iran's agricultural sector—a topic that has received limited scholarly attention. While existing studies often address climate change or water security separately, this research uniquely examines their combined effects within the context of Iran, focusing on the sector-specific challenges of agriculture. It identifies the lack of localized strategies tailored to Iran's unique climatic, socio-economic, and governance realities as a key research gap (Mansouri Daneshvar *et al*., 2019; Mirzaei *et al*., 2019).

Additionally, the study highlights the underexplored potential of integrating recycled water (NEWater) (highly treated reclaimed wastewater through microfiltration, reverse osmosis and ultraviolet radiation by brand name of NEWater) technologies into Iran's agricultural practices, drawing on international examples such as those implemented in Singapore and Namibia (Tortajada and van Rensburg, 2019). By doing so, it bridges the gap between global best practices and local applicability. Furthermore, the research incorporates socio-economic and policy dimensions, addressing gaps in the governance and planning frameworks that currently hinder optimal water resource management in Iran (Jamali Jaghdani and Kvartiuk, 2021). This comprehensive approach positions the study as a critical contribution to the discourse on sustainable water management in arid and semi-arid regions.

Climate change has had significant impacts on Iran, manifested in rising temperatures, altered precipitation patterns, increased frequency of droughts, sudden floods, and intensified dust storms. Over the past three decades, the average temperature in Iran has increased by approximately 1°C per decade, with projections indicating a further rise of 2.6°C by the end of the century. This steady increase in temperature has accelerated evaporation rates, exacerbating water shortages nationwide.

Precipitation patterns have also undergone significant shifts. Around 67% of climate stations in Iran report decreasing annual rainfall, with regions in the northern and northwestern parts of the country experiencing declines of up to 15% in yearly precipitation. Conversely, short-term, intense rainfall events have increased in arid and semi-arid regions, leading to flash floods. Recent data reveals that 50% of monitored stations have recorded an increase in 24-hour maximum precipitation, causing devastating floods that affect urban infrastructure and agricultural productivity (Salehi *et al*., 2020).

Droughts have become more frequent and prolonged, impacting over 90% of the country to varying degrees. Between 2001 and 2022, Iran experienced an unprecedented reduction in groundwater reserves, losing approximately 130 billion cubic meters, primarily due to unsustainable agricultural practices. This decline has placed additional strain on food security and rural livelihoods (Barati *et al*., 2023). These reductions in precipitation, groundwater, and renewable resources underscore the urgent need for targeted climate adaptation strategies. Addressing these challenges will require a multidimensional approach that integrates advanced water management practices, effective governance, and community-level interventions.

This article explores the challenges of climate change and water security in Iran's agricultural sector, aiming to identify optimal strategies for managing water consumption in the face of escalating climate change and water insecurity. As climate change is expected to result in decreased rainfall and increased temperatures in the coming years, implementing effective water management strategies in agriculture. To achieve this, the article first introduces the concept of water security, followed by an examination of its implications within the context of climate change in Iran. It then highlights the significance and extent of water consumption in Iran's agricultural sector. Finally, the article discusses key strategies for enhancing water resource management in the country.

MATERIALS AND METHODS

This research adopts a comprehensive and innovative methodology to address the challenges of water security and climate change within Iran's agricultural sector. A qualitative approach is utilized, combining systematic review, discourse analysis, scenario modeling, and stakeholder analysis to provide a multidimensional perspective.

During the data collection phase, both primary and secondary data are gathered from various sources. A systematic review of academic articles and reports is conducted to understand the relationship between Human-Environment Systems (HES) and water security in the context of climate change. In total, 68 articles were reviewed and analyzed to understand the interplay between HES and water security in the context of climate change, with 22 of these specifically exploring how human activities, such as agricultural practices, groundwater extraction, and governance frameworks, affect environmental feedback loops and the sustainability of water resources. The review also emphasizes the role of advanced irrigation technologies, governance reforms, and climate-resilient agricultural practices in improving water security under changing climatic conditions. By synthesizing these perspectives, the study establishes the HES framework as a conceptual foundation for exploring adaptive, resilient, and context-specific water resource management strategies. Additionally, semi-structured interviews were conducted with experts in agriculture, climate change, and water policy to gather specialized insights and indigenous knowledge. Quantitative and statistical data—including temperature fluctuations, precipitation patterns, and agricultural water consumption—were sourced from national and international organizations, providing a solid empirical foundation for the study.

In the analysis phase, discourse analysis was applied to policy documents, academic literature, and media reports, revealing patterns, contradictions, and thematic trends related to water security and agriculture in Iran. Scenario modeling was employed to simulate the impacts of climate change on water productivity and agricultural practices, with projections for temperature increases and reduced precipitation. Moreover, stakeholder network analysis examined the interactions and influence of key actors, such as government agencies, farmers, and the private sector, to understand their roles in water management.

The final stage of the research focuses on the development of practical and sustainable solutions. A policy framework is proposed to optimize water resource management in agriculture, emphasizing the adoption of advanced technologies, modern irrigation systems, and water recycling methods such as NEWater. These solutions are validated through expert consultations and feedback from key stakeholders. To enhance resilience, adaptive decision-making tools are developed to assist policymakers in responding to rapidly changing climatic conditions.

This research is innovative in several ways. First, it integrates multiple analytical methods to offer a holistic understanding of the challenges. Secondly, it bridges global best practices, such as NEWater technologies, with localized solutions tailored to Iran's specific context. Thirdly, it adopts a participatory approach by incorporating the perspectives and interactions of various stakeholders. By addressing current challenges and proposing forward-looking strategies, this study makes a significant contribution to the discourse on sustainable water management in arid and semi-arid regions.

A scoping review was seen as a method for synthesizing evidence-based research, focusing on identifying research priorities and gaps to inform policy reviews and future studies (Hosea and Khalema, 2020). This approach allows complex issues or under-examined topics to be treated as specific projects (Gutierrez-Bucheli *et al*., 2022). The scoping review led to the compilation of grey literature, studies, and available online reviews on "climate change," "water security," and "Iranian agriculture," sourced from Scopus and other scholarly search engines. Using these keywords, the search revealed 460,847 articles related to climate change, of which 120,165 discussed both climate change and water. Of these, only 5,252 articles addressed the intersection of water security and climate change. When focusing specifically on Iran, just 68 articles covered both climate change and water security in the Iranian context. Furthermore, 24 of these articles incorporated an agricultural dimension in their discussion of climate change and water security in Iran (See https://www-scopus-com). A purposive sampling technique was employed to ensure the inclusion of high-quality, contextually relevant studies. Articles were selected based on their geographical focus on Iran, methodological rigor, and relevance to the themes of climate change, water security, and agricultural practices. Additionally, local studies and reports were incorporated to capture region-specific insights and challenges.

RESULTS

Climate Change in Iran

Temperature and precipitation are two of the most critical climatic parameters influencing food production in Iran. Among countries in the west Asia, Iran is projected to experience a 2.6°C rise in mean temperatures and a 35% decline in precipitation over the coming decades (Mansouri Daneshvar *et al*., 2019). Evidence shows that Iran, like many other countries, has witnessed rapid warming in recent decades. Using meteorological data from fifteen ground stations across Iran over a 63-year period (1951–2013), Alizadeh-Choobari and Najafi (2017) examined minimum, maximum, and daily near-surface air temperatures. Their findings indicated that annual minimum, maximum, and average near-surface air temperatures have all increased in most regions of Iran. Thus, it can be concluded that Iran, like most countries, has been warming rapidly over the past few decades. In particular, temperatures in many regions of Iran began to show a significant shift in the 1980s or 1990s, with average temperatures rising by approximately 1.2°C after these turning points (Alizadeh-Choobari and Najafi, 2017).

As a result of this warming, Iran has experienced a downward trend in annual precipitation. The decrease in precipitation, coupled with rising temperatures, suggests

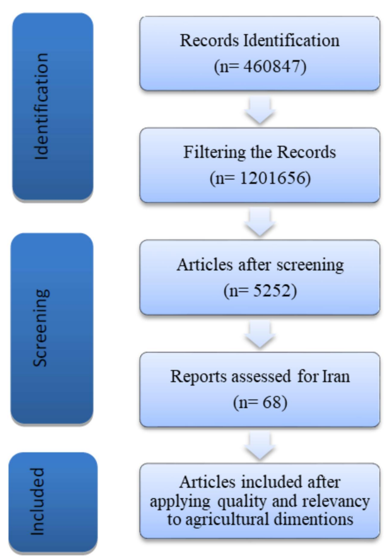

Figure 1. Preferred Reporting Items for Systematic Reviews flow chart for the systematic literature review.

that Iran has become drier and more vulnerable to droughts in recent decades (Alizadeh-Choobari and Najafi, 2017). Additionally, Bazrkar *et al*. (2015) predicted an increase in monthly temperatures for Iran in the coming years, based on the IPCC's SRES scenarios.

When considering precipitation, several critical parameters influence food production, such as the quantity and variability of rainfall. In Iran, annual precipitation is declining at 67% of climate stations, while 50% of the stations are experiencing an increase in the 24-hour maximum precipitation (Salehi *et al*., 2020; Bazrkar *et al*., 2015). The decline in annual rainfall is most prominent in northern and northwestern regions, while the increase in maximum 24-hour rainfall is observed mainly in arid and semi-arid areas. Although regional variations in annual precipitation are substantial, they are insufficient to compensate for the increasing 24-hour rainfall events. These changing precipitation patterns began in the 1970s across most climate stations, signaling the initial stages of climate change in Iran.

The decreasing annual precipitation could eventually lead to significant changes in Iran's water supply, particularly increasing demand for agricultural and urban water in arid and semi-arid regions. Conversely, the increasing intensity of 24-hour maximum rainfall poses a risk of accelerating soil degradation, which could contribute to desertification in these already vulnerable areas.

Recent studies highlight the growing prevalence of rainfall variability and climate change in Iran, which has resulted in more frequent floods and droughts, the two most significant climate-related challenges affecting food production (Vaghefi *et al*., 2019). Abeysekera *et al*. (2015) observed substantial increases in rainfall variability in the dry zones during both cultivation seasons. These changes led to fluctuations in moisture conditions during the reproductive stage of crops, impacting both the quantity and quality of crop yields. A recent study also showed an increase in extreme rainfall during the cropping season, which can result in excessive humidity during critical stages of crop development, ultimately affecting yield quality and quantity (Abeysekera *et al*., 2015).

Extreme precipitation events have become critical factors in managing erosion and flood risks. Maleksaeidi *et al*. (2021) note that, over the past years (2013–2017), extreme weather events with varying impacts on crop production have become more frequent. Rice, a staple crop that accounts for 15% of Iran's agricultural production, has been particularly affected. A comparison between agricultural production data from 2011–2012 and 2018–2019 reveals a troubling trend: agricultural production in Iran has stagnated, and the agricultural sector's share of the GDP is expected to decrease significantly. The studies conducted in western Iran further indicate water scarcity and low productivity, with environmental and climate-related disasters identified as the major concerns of participants—two of which are directly linked to climate change (Maleksaeidi *et al*., 2021).

According to Iran Meteorological Organization, the average surface temperature in Iran has risen by 1 to 1.5°C over the past 30 years, with an average increase of approximately 0.05°C per year. Each 1°C increase in temperature results in a 5-7% rise in evapotranspiration. Iran currently has around 106 billion m^3 of renewable water, with 75% lost to evapotranspiration, 16% as runoff, and 8% percolating into aquifers. However, only 30% of this renewable water is accessible, amounting to around 31 b.m^3. Over the next 50 years, annual precipitation is projected to decline from approximately 357 to 218 b m^3. Groundwater and renewable water resources are expected to decrease significantly, from 45.7 and 106 b m^3, respectively, to 8.64 and 37.9 b m^3. This disparity between the projected 38.9% decline in precipitation and the 81 and 64% reductions in groundwater and renewable resources indicates a future intensification of water scarcity (Barati *et al*., 2023; Cline, 2007; Mansouri Daneshvar *et al*., 2019; Babaeian *et al*., 2015). Figure 2 illustrates the predicted climate change scenarios.

The implications of this decline in precipitation, coupled with rising temperatures, cannot be overstated. Water insecurity is becoming increasingly probable (Patrick, 2021). Consequently, the effects of climate change on food production and agricultural sector at large are emerging as critical policy and security issues.

Water Security in Iran

Water security is defined in various ways across cultural, academic, and practical contexts. At the Second World Water Forum in March 2000, held in The Hague, water security was characterized as the enhancement and protection of freshwater and coastal ecosystems, promoting sustainable development and political stability. It also involves ensuring safe and affordable water for all and protecting vulnerable populations from water-related hazards.

The Centre for Water Security defines water security as the ability of communities to maintain access to sufficient, quality water for human and ecosystem health, while efficiently protecting lives and property from water hazards (Centre for Water Security, 2014). Similarly, the UN (United Nations, 2013) emphasizes the importance of water security in ensuring sustainable livelihoods, promoting socio-economic development, preserving ecosystems, and ensuring stability. The UN's definition focuses on adequate water access to sustain livelihoods while safeguarding against pollution and water-related disasters.

Despite these varying definitions, they all aim to ensure access to safe and quality water for both social and economic needs. However, achieving consensus on water security at the transnational level remains challenging due to the lack of authoritative international legal frameworks and competing national interests. The diverse uses of water—along with the significance of local context and cultural perspectives—

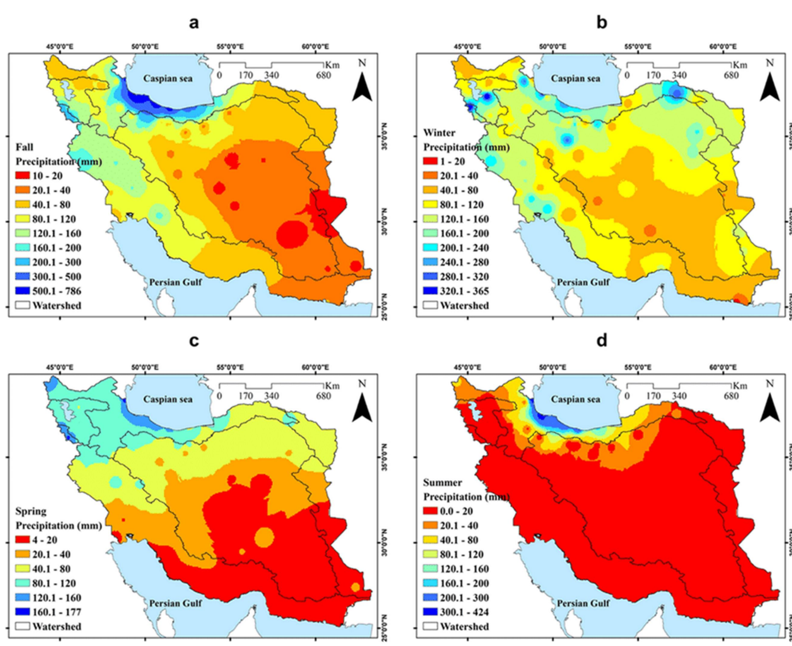

Figure 2. Long-term (2020 - 2050) mean precipitation in Iran (Behzadi *et al*., 2022).

further complicate this understanding. Consequently, a comprehensive approach to defining and achieving water security is essential.

The Middle East, situated in an arid and semi-arid region, faces significant water security challenges exacerbated by the effects of climate change (Sowers, Vengosh and Weinthal, 2011; Lelieveld *et al*., 2012; Osman *et al*., 2017; Mansouri Daneshvar *et al*., 2019; Nazemi *et al*., 2020). Researchers have linked drought-induced water scarcity to political unrest and social instability, particularly in Syria (Kelley *et al*., 2015; Almer *et al*., 2017), as well as in Afghanistan and Iran (Dehgan *et al*., 2014). Also, researchers determined the water security indicators and the situation of water security in Iran and their main watersheds (Zakeri *et al*., 2022). Several studies have examined the complex interplay between water scarcity, drought, and conflict in the region, highlighting the potential for water shortages to escalate tensions and trigger conflicts (Gleick, 2014; Michel, 2020; Czulda, 2022).

Iran faces severe water shortages and significant climate change impacts, which are further exacerbated by challenges in water management and increasing consumption (Danaei *et al*., 2019; Mirzaei *et al*., 2019; Gürsoy and Jacques, 2014). Poor management practices, including excessive groundwater extraction, dam overflows, and inadequate wastewater treatment have brought Iran closer to the brink of "water bankruptcy" (Mirzaei *et al*., 2019). These challenges threaten national security, as rising water stress may heighten the potential for conflicts (Farinosi *et al*., 2018).

Iran’s agricultural self-sufficiency projects, initiated as a response to economic sanctions, present a dilemma for water security. While these projects are essential for ensuring food independence, they place significant strain on the country's renewable water resources due to excessive consumption driven by heavily subsidized water use (Jamali Jaghdani and Kvartiuk, 2021). Policymakers must find a balance between achieving agricultural independence and maintaining sustainable water use. This balance will require reforms that promote advanced agricultural technologies, reduce water consumption, and optimize crop production.

Historically, water in Iran has been used for agriculture, industry, and domestic purposes. Biswas and Tortajada (2022) argue that ensuring water security requires addressing the long-term needs of all these sectors. This article reviews the historical context of water consumption in Iran, focusing particularly on agricultural use and the role of climate change in shaping water security challenges.

Water security is a multifaceted concept, encompassing a variety of indicators that measure the availability, quality, efficiency, and sustainability of water resources. This section explores the key water security indicators, their calculation methodologies, and their implications for water management in Iran, as well as providing comparative insights from both developing and developed countries.

Key Indicators and Their Methodologies

Per Capita Water Availability

This indicator measures the total renewable freshwater resources divided by the population. In Iran, per capita water availability has decreased from 7,000 m^3 in 1956 to less than 1,400 m^3 in recent years, crossing the water stress threshold of 1,700 m^3 per capita (UNESCO, 2021). This sharp decline is attributed to rapid population growth and overexploitation of water resources.

Agricultural Water Use Efficiency

Defined as the ratio of water effectively used by crops to the total water applied, this indicator highlights irrigation inefficiencies.

In Iran, irrigation efficiency averages 35%, significantly lower than in the developed countries such as Australia and the United States, where efficiencies range between 70–90% due to the adoption of modern technologies like drip and precision irrigation (Mirzaei *et al*., 2019).

Groundwater Depletion Rates

Groundwater resources are crucial for Iran, accounting for over 50% of its agricultural water supply. Between 2001 and 2021, Iran lost approximately 130 B.m^3 of groundwater due to unsustainable extraction (Nazari *et al*., 2020). By comparison, developed countries have implemented strict regulations and monitoring systems to control groundwater usage, reducing depletion rates significantly.

Water Recycling and Reuse

This indicator reflects the percentage of wastewater treated and reused for agricultural, industrial, or domestic purposes. Iran recycles less than 10% of its wastewater, whereas countries like Singapore have achieved recycling rates of over 30% through technologies like NEWater, ensuring a sustainable water supply (Tortajada and van Rensburg, 2019). Developing countries like Iran face significant challenges in achieving water security compared to developed nations. The key differences lie in the followings:

- Technological Integration: Developed countries widely adopt advanced technologies such as precision irrigation, desalination, and water recycling. In contrast, developing countries struggle with limited financial resources and access to such innovations.
- Policy and Governance: Developed nations have established robust governance frameworks to regulate water use and enforce sustainability practices, whereas developing countries often face fragmented policies and weak enforcement mechanisms.
- Climate Resilience: Developed countries have invested in adaptive measures to combat climate change impacts, while developing nations like Iran are more vulnerable due to inadequate infrastructure and limited financial support.

These comparisons underscore the need for tailored approaches in addressing water security. For Iran, improving irrigation efficiency and implementing wastewater recycling programs can bridge the gap, while effective governance reforms can create an enabling environment for sustainable water management.

Water Consumption in Iran's Agricultural Sector

Globally, water consumption in Iran’s agricultural sector is among the highest, accounting for over 90% of the country's freshwater resources (Nazari *et al*., 2018). Rural households are heavily dependent on agriculture, which remains largely traditional and is supported by government subsidies for inexpensive water. Despite agriculture contributing only about 10% of Iran’s GDP, it remains the dominant user of water, far exceeding the global average for renewable water resources. However, Iran's annual rainfall is less than one-third of the global average, resulting in unsustainable groundwater extraction across all provinces (Golian *et al*., 2021).

This growing groundwater depletion, often referred to as a sign of "water bankruptcy," poses a significant threat to Iran’s long-term food security (Mirzaei *et al*., 2019). Groundwater storage has dramatically declined, with some regions losing up to −4,400 Mm^3 between 2002 and 2017 (Safdari *et al*., 2022). The situation is exacerbated by increased agricultural water use, which reached 103 $B.m^3$ in 2021, far surpassing the national water consumption estimate of 88.5 $B.m^3$ (Yousefi *et al*., 2021).

Although the agricultural sector's share of total water consumption has been gradually decreasing, the absolute demand continues to rise. This trend, which began around 2013, is evident in Figure 3, which shows that despite attempts to curb overall consumption, agricultural water demand remains on an upward trajectory. With 90% of Iran's freshwater allocated to agriculture and an irrigation efficiency of only 35%, Iran lags behind developed countries, where irrigation systems typically achieve efficiencies between 70 and 90%. This inefficiency is a major challenge for Iran, especially when compared to international standards (Nazari *et al*., 2018; FAO, 2016). Currently, only 2.4 M.ha of Iran's total 16.5 M.ha of agricultural land benefit from modern irrigation systems.

The inefficiency of Iran's irrigation practices underscores the urgent need for modernization in agricultural water management. Critics, including Mirchi *et al*. (2010), and Islam and Madani (2017) point to significant failures in Iran's water management systems, which lack comprehensive planning that accounts for the ecological context of water use. Improved water management practices could allow Iran to achieve similar agricultural outputs with far less water consumption. Without substantial improvements, Iran faces a future where water scarcity—exacerbated by climate change and poor management—could severely affect its agricultural productivity and overall socio-economic stability.

NEWater, Continuous Return of Water to the Recycling Cycle

Technological advances illustrate that optimal water management can effectively mitigate water scarcity by recycling this vital resource (Tortajada and van Rensburg, 2019). Through efficient collection, treatment, and reuse of wastewater, treated water can be cycled back into consumption, including drinking water, without limitations on quality or quantity. NEWater refers to high-grade reclaimed water produced through advanced purification processes, including microfiltration, reverse osmosis, and ultraviolet disinfection. This technology, pioneered in Singapore, recycles wastewater into potable water, significantly reducing dependency on traditional freshwater sources. In the context of this study, NEWater serves as a potential model for addressing water scarcity in Iran through wastewater recycling. Successful examples

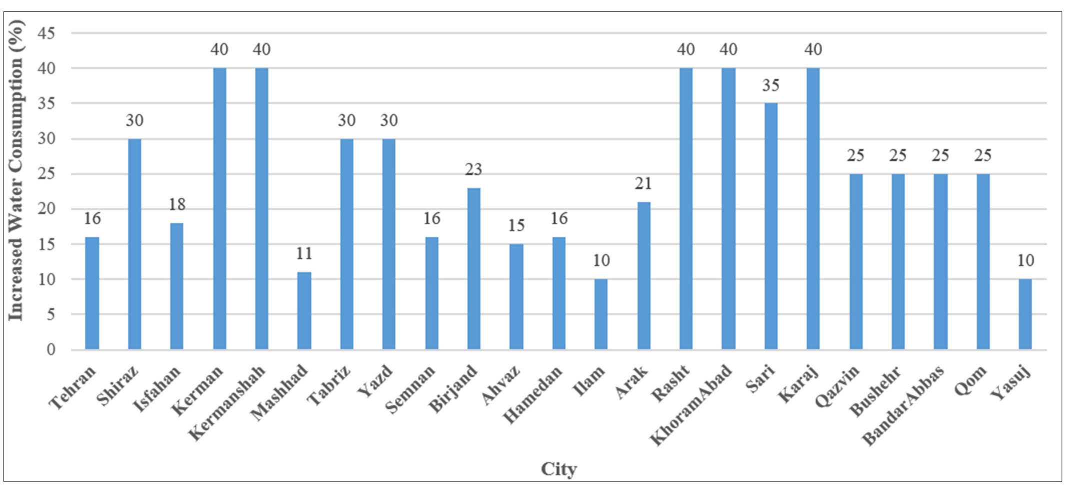

Figure 3. Increased water consumption in Iran in different states (Iran's Energy Balance, 2020).

of this practice exist worldwide, one notable case being Windhoek, Namibia, where innovative management of domestic wastewater has resolved long-standing drinking water issues over the past 50 years. Despite Namibia's arid conditions, its citizens have reported no health problems from using recycled drinking water (Tortajada and van Rensburg, 2020).

While Namibia may not be well-known in Iran, its leadership in recycled water use offers valuable lessons. Singapore is another exemplary case, with over 30% of its water demand met through recycled sources. Countries like Japan, Germany, and US (California) have also adopted similar strategies (Voulvoulis, 2018; EPA, 2017). Despite these successes, public acceptance of recycled water, especially NEWater, which is perceived as superior to regular tap water, remains a challenge due to psychological barriers (Bai *et al*., 2020; Tortajada and Buurman, 2017). This reluctance has generated significant opposition, ultimately causing the U.S. government to halt major recycled water initiatives (Hartley, 2006).

In Iran, the total municipal wastewater generated is 6.5 b m^3 annually, with only 42% treated and recycled, raising environmental and public health concerns. The conventional activated sludge process dominates this treatment, and operational costs average \$0.20 per cubic meter (FAO, 2017). With total water withdrawal in Iran estimated at 93.3 billion cubic meters per year, treating wastewater could fulfill 6% of the nation's water needs.

Reducing water consumption positively impacts the environment by lowering energy use and greenhouse gas emissions, which is particularly crucial in the context of climate change. While it is challenging to quantify the precise effects of a 6% reduction in water usage, it is evident that this strategy is vital for ensuring sustainable water supplies and mitigating climate impacts in Iran.

Importance of Human-Environmental System in Increasing Water Security against Climate Change

Human-Environmental Systems (HES) are complex, paired systems that require specialized methods and interdisciplinary approaches to understand and manage. Human-environmental interactions represent the difference between harmful and beneficial interactions (Pahl-Wostl, 2015). Figure 4 shows the HES framework for water security. This framework and its relevant principles are designed to facilitate

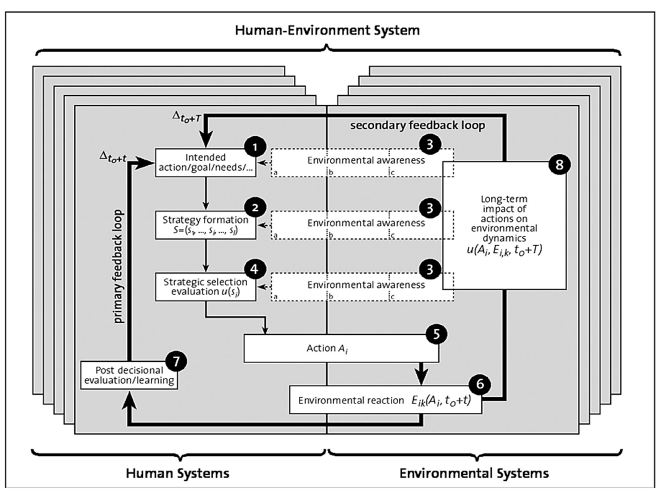

Figure 4. HES framework of water security.

research on and address complex human-environmental issues. Typically, in the early stages of tackling a complex environmental problem, the issue often appears unstructured and cannot always be clearly defined. The principles identified in the HES framework (denoted by numbers) serve as key elements for understanding and transforming the water security issue.

The framework adopts a hierarchical view of the human system. At each hierarchical level, different regulatory mechanisms are in place concerning the environmental system. Understanding these mechanisms helps identify intervening regulatory mechanisms. The framework also focuses on the conceptualization of human behavior through goal setting, strategy selection, action, and learning, with particular attention to immediate (primary) and delayed (secondary) responses to the environmental system.

In this context, and according to the definition of water security, awareness of human and environmental stimuli, along with the primary and secondary feedback loops between the human and environmental systems, results from the interaction between ecosystem services, such as the production and supply of water—and environmental hazards, such as floods and droughts. These interactions ultimately influence the strategies adopted to ensure water security in the basin (Scholz, 2011).

The research findings provide a structured foundation that logically leads to the model presented in Figure 4, illustrating the interconnectedness of human-environmental systems (HES) and their relevance to water security in Iran's agricultural sector. The findings identify critical challenges such as the impacts of climate change, including rising temperatures and reduced precipitation, water insecurity, inefficient irrigation practices, and governance shortcomings. These challenges highlight the complexity of interactions between human and environmental factors, which is central to the HES model.

The study demonstrates how human activities, such as over-extraction of groundwater and reliance on traditional agricultural methods, exacerbate environmental stress. These interactions are captured in the HES model, which links human goals (e.g., achieving food security) with environmental constraints (e.g., water scarcity). Furthermore, the research underscores the need for holistic solutions, such as improving irrigation efficiency, adopting water recycling technologies like NEWater, and reforming governance structures. These solutions align closely with the principles of the HES model, which emphasizes feedback loops and regulatory mechanisms between human and environmental systems.

By proposing actionable strategies, such as better water management, technological adoption, and farmer education, the findings align with the hierarchical structure and feedback-based approach of the HES model. The review also highlights the critical role of the human-environmental system (HES) in addressing water security challenges in the context of climate change. Human activities, such as unsustainable irrigation practices and groundwater over-extraction, have intensified environmental stressors, thereby reducing water availability. Conversely, the implementation of advanced technologies (e.g., precision irrigation and water recycling systems) demonstrates how human interventions can mitigate these impacts.

The reviewed studies highlight feedback loops within the HES framework, where climate changes exacerbate agricultural water demand, and inefficient human responses further degrade the environment. For instance, 75% of the analyzed articles identified groundwater depletion as a direct consequence of unregulated extraction, while 60% emphasized the potential of governance reforms to create adaptive water management systems. These findings underscore the importance of integrating human-environmental systems into water resource management strategies to enhance resilience against climate change.

DISCUSSION

This study examines the critical challenges of water security in Iran's agricultural sector, particularly in the context of climate change. The findings highlight the significant risks posed by the rising air temperatures, reduced precipitation, and inefficient water management practices. Climate change exacerbates existing vulnerabilities in the agricultural sector, including heavy reliance on groundwater and outdated irrigation methods, which collectively account for over 90% of freshwater consumption in Iran.

The research emphasizes the urgent need for adopting modern irrigation systems to address these inefficiencies, as Iran's current irrigation efficiency is only 35%, well below global standards. Technological solutions, such as water recycling (e.g., NEWater) and the expansion of greenhouse cultivation, offer promising strategies to reduce water demand while maintaining agricultural productivity. However, implementing these solutions requires robust governance reforms to regulate water usage, curb illegal activities like unregulated well drilling, and optimize resource allocation.

Additionally, the study stresses the importance of localized approaches to water resource management, considering Iran's diverse regional climates and socio-economic conditions. Addressing these challenges necessitates collaborative efforts from policymakers, farmers, and the private sector to implement sustainable practices, enhance farmer education on advanced techniques, and foster innovation in agriculture.

In conclusion, this research underscores the interconnected nature of climate change and water security challenges in Iran's agricultural sector. By adopting a holistic approach, incorporating technological advancements, governance reforms, and sustainable practices, Iran can mitigate the impacts of climate change and ensure the long-term sustainability of its agricultural sector. These actions are essential for maintaining food security and preserving vital water resources for future generations. A conceptual summary of the research findings is presented in Table 1.

Also, some of the most important effective ways to improve water security in Iran's agricultural sector in the current water shortage situation can be introduced as follows:

- Lack of a specific cultivation pattern in the country based on the National Agricultural Plan,
- Quantitative and qualitative development of greenhouse cultivation,
- Transferring the growing season of some agricultural products from spring to autumn and winter,
- Increase the use of modern irrigation systems and educate farmers in this regard,
- Repair of canals,
- Preventing the drilling of illegal wells
- Consolidation of agricultural lands in one area,
- Modification of the traditional pattern of agricultural water consumption,
- Prevent contamination of surface and groundwater resources,
- Attention to climate diversity in water resources management,
- Utilizing operational research in order to achieve the goal of reducing the level and increasing agricultural production,
- Paying attention to the production of strategic products for the country's self-sufficiency,

Table 1. Comprehensive summary of research findings.

Dimension	Findings	Implications
Climate Change Impact	- Mean temperature to rise by 2.6°C by 2100. - Precipitation decline of 35%, leading to intensified droughts and floods.	- Reduced water availability for agriculture. - Increased vulnerability of crops to extreme weather.
Water Usage in Agriculture	- 90% of water is consumed in agriculture. - Groundwater depletion at alarming rates (e.g., -4400 Mm^3 between 2002-2017).	- Threatens long-term food security. - Risks of desertification and land subsidence.
Irrigation Efficiency	- Current efficiency is ~35% vs. 70-90% in developed nations. - Only 2.4 million hectares use modern methods out of 16.5 million hectares of farmland.	- High water wastage. - Immediate need for adoption of advanced irrigation techniques.
Governance Challenges	- Lack of specific cultivation patterns aligned with National Agricultural Plans. - Weak enforcement of water usage laws and excessive subsidies.	- Unsustainable agricultural practices persist. - Potential for socio-economic conflicts.
Technological Gaps	- Recycling municipal wastewater only meets 6% of national water needs. - Low adoption of technologies like NEWater.	- Missed opportunities for sustainable water management.
Socio-Economic Factors	- Limited private sector investment due to government price controls. - Farmers lack knowledge in advanced agricultural methods.	- Stagnation in productivity and innovation. - Inefficiency in resource allocation.

- Quantitative and qualitative development of conversion industries in the agricultural sector,
- Improving the quality and nutritional value of products produced,
- Use of intelligent methods to store water in dry areas and
- Use of soilless or hydroponic cultivation methods.

This article underscores the critical importance of effective water resource management in ensuring water security in Iran's agricultural sector. It emphasizes that improving water management practices is directly linked to Iran's ability to secure adequate water for its agricultural needs. The article also highlights the potential of strategies such as NEWater, a water recycling initiative, to enhance water management in the agricultural sector.

Moreover, the article stresses the necessity for long-term planning and a sustained commitment from government officials to prioritize water security within agriculture. While short-term and medium-term solutions are essential, the article argues that long-term plans are crucial to address water security effectively. This requires a shift from seeking immediate responses to embracing a more sustained strategic approach.

In addition to long-term planning, the article advocates for promoting a culture of optimal water consumption within the agricultural sector. This includes improving the cultural infrastructure around water usage and conducting national research to develop cultivation models better suited to Iran's diverse climatic conditions. By integrating these measures, along with strengthening law enforcement, the article posits that water security in Iran's agricultural sector can be achieved in the future.

CONCLUSIONS

Based on the research findings, several recommendations are put forward for future studies aimed at tackling water security challenges in Iran's agricultural sector. Future research should focus on regional water management, recognizing the varied climatic and agricultural conditions across Iran. Comparative studies could help develop tailored strategies for sustainable water use in different regions. Additionally, research into the impact of modern irrigation technologies, such as drip and sprinkler systems, on water use efficiency and crop yields is essential. Field trials and case studies would provide valuable insights into the feasibility and scalability of these methods. Integrating renewable energy sources like solar and wind power into water recycling and desalination processes is another critical area for investigation. This could improve the sustainability of water management systems while reducing reliance on conventional energy. Furthermore, future studies should include economic analyses of agricultural water subsidies to evaluate their effects on water consumption, agricultural productivity, and farmers' incomes. This would provide a foundation for potential policy reforms aimed at improving water use efficiency. Understanding farmers' attitudes toward adopting advanced technologies and sustainable practices is equally important. Research could assess the effectiveness of training programs and identify barriers to behavioral change. Additionally, developing and testing climate-resilient crop varieties that require less water and are better suited to Iran's changing climate is a promising area for innovation. Time series analyses studies on the implementation of water recycling technologies, such as NEWater, would provide insights into their environmental, economic, and health impacts over time. Moreover, evaluating the effectiveness of existing water governance frameworks and proposing integrated models involving local, regional, and national stakeholders could strengthen policy and management systems. These recommendations address the gaps identified in the study and offer valuable directions for advancing both knowledge and practical solutions to ensure sustainable water security in Iran's agricultural sector.

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راهبردهای افزایش امنیت آب در بخش کشاورزی ایران در شرایط تغییر اقلیم

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چکیده

موضوع تغییرات اقلیمی و چالش‌های امنیتی مرتبط با آن به نگرانی فزاینده‌ای برای ایران به‌ویژه در بخش کشاورزی تبدیل شده است. افزایش جمعیت، افزایش تقاضا برای محصولات کشاورزی و نیاز به امنیت غذایی این چالش ها را تشدید می کند. این مطالعه خطرات ناشی از کاهش بارندگی، افزایش دما، و شیوه‌های مدیریت ناکارآمد آب، از جمله وابستگی شدید به آب‌های زیرزمینی و سیستم‌های آبیاری قدیمی را برجسته می‌کند. این بر نیاز فوری به فن‌آوری‌های آبیاری مدرن، مانند بازیافت آب (NEWater)، و اصلاحات قوی حکمرانی برای بهبود کارایی مصرف آب، که از طریق چارچوب HES تحلیل می‌شود، تأکید می‌کند. این مطالعه نتیجه‌گیری می‌کند که اتخاذ یک استراتژی جامع و بلندمدت، ترکیب نوآوری‌های فن‌آوری، شیوه‌های مدیریت محلی آب و حکمرانی تقویت‌شده، می‌تواند اثرات تغییر اقلیم را کاهش داده و استفاده پایدار از منابع آب را در بخش کشاورزی ایران تضمین کند.