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Sustainable Water Resources Management in Agriculture: Challenges, Technological Innovations, and Future Perspective

Tarımsal Su Kaynaklarının Sürdürülebilir Yönetimi: Sınırlılıklar, Teknolojik Yenilikler ve Gelecek Perspektifleri

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Abstract

One of the most significant turning points in human history was the establishment of an agriculture-based society. Approximately 5000 years ago, thanks to agricultural irrigation, the greatest civilizations of their time emerged in Mesopotamia. Despite constructing hydraulic structures of remarkable sophistication and organization for their era, these civilizations eventually collapsed due to inadequacies in sustainable irrigation management. Nearly 5,000 years later, another agricultural revolution, known as the “Green Revolution,” took place. The consequences of this latter revolution are still strongly felt today, particularly through its adverse impacts on soil and water resources. Fortunately, in order to prevent history from repeating itself, the international community has focused on sustainability and held landmark conferences. During this process, a substantial body of scientific knowledge on sustainable irrigation has been developed. If the technological opportunities that have arisen from this knowledge can be effectively utilized as tools for sustainable irrigation management, a critical step will be taken toward achieving this challenging goal. In this context, the study focuses on agricultural water management as the most crucial component of sustainable water resources management; it examines, within a comprehensive framework, the historical evidence for the importance of sustainable water governance, the extent of salinity problems, the freshwater resources of

Türkiye and the world, the major international conferences on sustainable water management, and the technological opportunities in sustainable agricultural water management.

Keywords: Sustainable water management, agricultural water management, sustainable irrigation, agricultural technology, sustainable development

Özet

İnsanlık tarihinin en önemli dönüm noktalarından biri, tarıma dayalı düzenin kurulması ile yaşanmıştır. Yaklaşık 5000 yıl önce Mezopotamya topraklarında tarımsal sulama sayesinde çağın en büyük medeniyetleri ortaya çıkmıştır. Bu medeniyetler, zamanlarına göre olağanüstü sayılabilecek yetkinlikte ve organizasyonda hidrolik yapılar inşa etmelerine rağmen, sürdürülebilir sulama yönetimindeki yetersizlikler nedeniyle yok olmuşlardır. Yaklaşık 5000 yıl sonra "Yeşil Devrim" adıyla bilinen başka bir tarım devrimi daha yaşanmıştır. Bu son devrimin sonuçları, özellikle su ve toprak kaynaklarına olan olumsuz etkileriyle günümüzde yakından hissedilmektedir. Neyse ki, tarihin tekerrür etmesini önlemek amacıyla uluslararası toplum sürdürülebilirlik konusuna odaklanmış ve ses getiren toplantılara imza atmıştır. Bu süreçte özellikle sürdürülebilir sulama alanında büyük bir bilimsel bilgi birikimi oluşmuştur. Bu bilgi birikimiyle gelişen teknolojik fırsatlar, sürdürülebilir sulama yönetimi için bir araç olarak kullanılabildiği takdirde, bu zorlu hedefe ulaşmada çok önemli bir adım atılmış olacaktır. Bu bağlamda, çalışmada su kaynaklarının sürdürülebilir yönetiminin en önemli bileşeni olan tarımsal su yönetimine odaklanılmış; tarihsel kanıtlarla su kaynaklarının sürdürülebilir yönetiminin önemi, tuzluluk problemlerinin boyutu, Türkiye'nin ve dünyanın tatlı su varlığı, uluslararası toplumun sürdürülebilir su yönetimi konusundaki önemli toplantıları ve sürdürülebilir tarımsal su yönetiminde teknoloji fırsatları bütüncül bir çerçevede incelenmiştir.

Anahtar kelimeler: Sürdürülebilir su yönetimi, tarımsal su yönetimi, sürdürülebilir sulama, tarım teknolojisi, sürdürülebilir kalkınma

Introduction

Water is of great importance not only for the survival of individuals but also for the course of human history. Throughout history, human settlements have always been associated with access to water. Although Mesopotamian civilizations demonstrated remarkable achievements in hydraulic engineering, their failure in irrigation management led to severe salinity problems, which became a decisive factor in their collapse. A similar pattern re-emerged with the "Green Revolution" of the mid-20th century. Technological advancements enabled the development of new crop varieties, pesticides, and fertilizers; however, their excessive use by "societies with access" has resulted in environmental impacts that are difficult to reverse.

Irrigation plays a crucial role in agricultural production, particularly in arid regions. Between 1970 and 1980, irrigated areas increased by 35%, making a substantial contribution to global food production. Since the 1980s, the expansion of irrigated land has slowed considerably. While the annual growth rate averaged 1.5% between 1950 and 1990, it was projected to decline to 0.6% during 1998–2003 (Siebert et al., 2015). According to the FAO's 2022 report, total irrigated areas expanded from 139 million hectares in 1961 to 328 million hectares in 2018, yet the pace of increase has declined since 2010. Irrigated areas provide significantly higher productivity and economic returns per unit area compared to rainfed agriculture; although they account for only 15% of global cultivated land, they meet 30–40% of the world's food demand (Ghassemi et al., 1995; Postel, 2000). As reported by FAO (2022), irrigated areas constitute 22% of the world's cultivated land while contributing nearly 40% of global production. In developing countries, cereal yields average 1.5 t/ha under rainfed conditions, whereas yields on irrigated areas reach 3.3 t/ha. Irrigation not only improves productivity but also increases cultivation intensity and encourages farmers to cultivate higher-value crops (Fuglie et al., 2020).

Agriculture represents the largest share of freshwater consumption both globally and nationally. Overexploitation of water resources is progressively reducing their availability in both quantity and quality. This situation necessitates the rational use of existing resources and the adoption of sustainable agricultural practices. In this context, developing alternative sources alongside the efficient use of water has become essential. Innovative approaches such as atmospheric water harvesting, integrated with sensor technologies, remote sensing, and artificial intelligence (AI)-based systems in irrigation management, stand out as critical tools for ensuring efficient water use. Recent studies have demonstrated the potential of atmospheric water harvesting as a complementary source for irrigation and rural water supply in arid and semi-arid regions (Fessehaye et al., 2014; Tu et al., 2018; Feng et al., 2022; Ahrestani et al., 2023). Similarly, remote sensing and AI-based models have been increasingly employed to monitor soil moisture, crop water use, and irrigation scheduling (Sánchez et al., 2016; Yang et al., 2020; Seyar and Ahamed, 2024). In this study, the concepts of water resources, water management, and sustainability are addressed at the global scale and within Türkiye, with particular attention given to the importance of technological applications in irrigation and to the assessment of strategies for future water management.

Water Availability

Water availability is generally assessed through two key parameters: total freshwater availability and per capita water potential. These parameters, in interaction with population, may result in significantly different rankings of water availability. For example, Iceland, with a population of 357000, ranks five times higher than Canada—which possesses nearly half of the world's freshwater resources—in terms of per capita water potential. This illustrates that rankings based on total water potential may differ considerably from those based on per capita availability (Öztürk and Çolak, 2024).

The global distribution of water resources use across continents is presented in Table 2.1. Although Asia appears relatively advantaged in this distribution, the continent is home to 60% of the world's population, rendering its water resources insufficient to meet demand. On average, global per capita water availability is estimated at 5000–6000 m³ per year (UN-Water, 2007). Falkenmark et al. (1989) proposed the "Falkenmark Water Stress Index" which defines thresholds for water scarcity. According to this index, countries with annual per capita freshwater availability below 1,700 m³ are considered water scarce. If this figure falls below 1000 m³, the country experiences water stress, and below 500 m³, absolute water scarcity occurs. Due to its simplicity, this classification has been widely applied in research (UNDP, 2006).

Table 2.1 Distribution of water resources by continent

Continent	Share of global water use (%)	Share of world population (%)
Asia	36	60
South America	25	6
North America	15	8
Africa	11	17
Europe	8	10
Ocenia	5	<1

In the last century, the world population has tripled while water consumption has increased sevenfold (USİAD, 2010; Şahin, 2016). However, uneven distribution of water resources prevents around 80 countries from meeting their water demand (USİAD, 2007). Currently, 700 million people in 43 countries suffer from water stress and scarcity (UNDP, 2006). According to UN-Water (2012), one billion people worldwide live below water stress thresholds. In Türkiye, per capita annual freshwater availability remains below both the global average and levels of developed countries (Gezer and Erdem, 2018).

A country's water availability is primarily shaped by precipitation, which is influenced by geographical location, topography, climate, and seasonal variations. Türkiye's water potential is summarized in Table 2.2. Of Türkiye's annual water potential of 112 billion m³ (due to usable surface water and safely extractable groundwater reserves), approximately 57 billion m³ is currently utilized. Sectoral allocation of this water indicates that 44 billion m³ (77%) is used for irrigation, while 13 billion m³ (23%) is allocated to domestic and industrial purposes (DSİ, 2022). Globally, these proportions are 70% and 30%, while in Europe they are 33% and 67% (Anonymous, 2018). The predominance of water use in agriculture makes this sector a critical focus for water-saving strategies in Türkiye (Öztürk and Çolak, 2024).

Table 2.2 Türkiye's annual water potential components (Anonymous, 2018)

Component	Quantity (billion m³)	Description/Source
Average annual precipitation	450	Corresponds to 574 mm
Surface runoff	185	Through rivers and lakes
Total groundwater reserves	23	18 billion m³ safely extractable
Usable surface water	94	Based on technical and economic conditions

According to Turkish Statistical Institute (TÜİK) 2021 data, the population was 84680273, with per capita annual usable water availability of 1323 m³. This places Türkiye among water-stressed countries. Projections estimate the population to reach 96498000 by 2050, reducing per capita water availability to 1161 m³/year—even if total water resources remain constant—classifying Türkiye as water-poor (DSİ, 2019; TÜİK, 2019). Recent droughts have caused significant issues in both agricultural and domestic water use, resulting in economic losses. Climate instabilities from global climate change are expected to exacerbate water scarcity, increasing social and economic challenges. Therefore, accurate monitoring of Türkiye's water availability and efficient water use are critical for future planning (Öztürk and Çolak, 2024).

The reduction of usable freshwater resources and the consequent risk of water scarcity represent one of the most pressing global challenges of the 21st century. Therefore, the primary goal of water resources management is to ensure efficient, planned, and economical use of this irreplaceable resource. Additionally, identifying and mitigating threats to water resources and protecting water-dependent ecosystems are essential. Sustainable water resources management is therefore of vital importance for all countries.

Water and Sustainable Agriculture

The development of sustainable agricultural practices has emerged as a critical requirement for ensuring global food security and the efficient use of natural resources. Achieving sustainability in agricultural production, in a manner that accommodates the pressures of a growing population and changing climatic conditions, necessitates the rational management of water and soil resources. In this context, sustainable agriculture regarded a cultivation approach that leverages technology to meet the needs of present societies while preserving and enhancing the capacity of future generations to meet their own requirements (Dhanaraju et al., 2022).

The direct impact of water on crop yield, especially in arid and semi-arid regions, links the sustainability of agricultural production and productivity closely to good agricultural practices. FAO (2014) defines sustainable agriculture as *"meeting the food and income needs of the present generation while conserving natural resources and securing the production capacity of future generations"* (Neven, 2014). Within this framework, water serves not only as a production input but also as a fundamental resource for maintaining ecosystem continuity. However, a significant portion of irrigation water is wasted, or irrigation planning is not effectively managed, preventing the achievement of potential yield levels (Pereira et al., 2012). Therefore, irrigation management within sustainable agriculture should not only focus on calculating the required irrigation water but also aim to enhance expertise in monitoring and measuring crop water use (evapotranspiration) and water deficit. This approach can improve the sustainability, productivity, and efficiency of water use. In this regard, the effective utilization of existing technologies, adaptation of new technologies to agricultural practices, and the development of crop and production management practices are of great importance. The Climate-Smart Agriculture (CSA) approach developed by FAO (2010) has emerged as a prominent framework in sustainability discussions. Other notable frameworks include Integrated Water Resources Management (IWRM), supported by the World Bank and the Global Water Partnership (GWP), and, increasingly, Nature-Based Solutions (NbS). Table 3.1 presents key approaches to water management in agriculture. These approaches, shaped under the leadership of international organizations such as FAO, GWP, and the World Bank, provide different frameworks to ensure sustainable water use and enhance productivity in agricultural production.

Table 3.1 Key approaches to water management in agriculture (scope and institutional actors)

Approach	Instutional actors	Scope	References
Agroecology	Academia since 1930s; FAO and farmer organizations after 1990s	Agriculture based on ecological principles; improving water and soil efficiency	Wezel et al., 2009
Integrated Water Resources Management (IWRM)	1992 Dublin Conference and Rio Summit; GWP and IWMI since 1996	Integrated management of water, soil, and ecosystems; basin-scale irrigation planning	GWP, 2000; Molden, 2007; UN-Water, 2024
Precision Agriculture (PA)	1990s, USA and Europe; private sector and universities	Satellite-, sensor-, and GPS-based irrigation and input optimization	Gebbers and Adamchuk, 2010
Sustainable Intensification (SI)	Early 2000s, UK science-policy initiatives	Higher yields with less water and inputs	Garnett et al., 2013
Ecosystem-based Adaptation (EbA)	Post-2008, supported by UNFCCC, CBD, IUCN, UNEP	Climate adaptation through forests and wetlands; supporting water cycles	Colls et al., 2009
Climate-Smart Agriculture (CSA)	Introduced by FAO in 2010; supported by World Bank and IFAD	Productivity, climate adaptation, and emission reduction in agriculture; centralizing water management	FAO, 2010
Water-Energy-Food Nexus (WEF Nexus)	2011 Bonn Conference, SEI	Holistic consideration of water, energy, and food policies	Hoff, 2011
Nature-based Solutions (NbS)	Post-2016, IUCN, UNEP, and European Union	Water storage, irrigation support, and sustainability through ecosystem services	Cohen-Shacham et al., 2016

Among the approaches listed in Table 3.1, the most prominent and widely accepted is the Integrated Water Resources Management (IWRM) approach. This approach considers water, land, and ecosystem resources holistically at the basin scale, aiming to achieve economic efficiency, social equity, and environmental sustainability simultaneously (Molden, 2007). IWRM is the most commonly adopted framework, and according to UN-Water (2024), its global implementation level has reached 57%. Successful applications of the IWRM framework have been reported in various regions, highlighting its adaptability under different socio-environmental contexts. For example, in the Durlung Watershed of Nepal, community-based participation and hydrological monitoring under IWRM principles improved local water governance and institutional collaboration (Khanna et al., 2016). Similarly, in the Ebro River Basin in Spain, basin-scale integration and stakeholder engagement enhanced sustainable water allocation and policy coordination (Bielsa and Cazcarro, 2014). Conversely, in the Middle Manyame Sub-Catchment of Zimbabwe, although IWRM-oriented legal and policy frameworks were established, limited technical capacity and economic constraints hindered full implementation (Hove et al., 2016). These case studies collectively demonstrate that the success of IWRM depends strongly on institutional coordination, stakeholder engagement, and socio-economic capacity. In Türkiye, this approach is defined as a strategic objective in the National Water Plan (2019–2023), the Water Efficiency Strategy Document (2023–2033), DSİ Strategic Plans, and other water management-related reports.

Precision Agriculture (PA) and Climate-Smart Agriculture (CSA) are among the approaches most frequently conflated. In both frameworks, technology is employed effectively to support sustainable agriculture. PA focuses on the precise application of all agricultural inputs (water, pesticides, fertilizers) in the right amount, at the right time, and in the right place, aiming to optimize input use. This not only enhances productivity but also contributes to reducing environmental impacts (Gebbers and Adamchuk, 2010). In contrast, CSA represents a broader framework that encompasses not only productivity improvement but also climate change adaptation and the reduction of greenhouse gas emissions (FAO, 2010; Lipper et al., 2014). Within CSA, water management plays central role and benefits from technologies developed for PA. Consequently, while PA primarily offers a technical application platform (Gebbers and Adamchuk, 2010), CSA constitutes a more comprehensive approach, integrating agricultural policies, climate strategies, and sustainable development objectives (Campbell et al., 2018).

Nature-based Solutions (NbS) are defined as a set of actions that leverage the functions of nature and ecosystem services to address societal challenges—such as climate change, water scarcity, disaster risks, food security, and biodiversity loss—while simultaneously providing benefits to biodiversity and human well-being (Cohen-Shacham et al., 2016). A bibliometric analysis conducted by Zyoud and Zyoud (2025) reported that scientific research on NbS is largely concentrated in European Union countries, with the United Kingdom, Italy, and Germany emerging as leading contributors. The study also highlighted that these research efforts are thematically clustered around urban resilience, hydrological risk management, and climate change mitigation.

In Türkiye's National Roadmap Report prepared for the UN Food Systems Summit (2021), water conservation, efficiency, and sustainable water management were identified as priority objectives. Within this framework, the widespread adoption of modern pressurized irrigation systems and increased use of smart technologies—including Internet of Things (IoT), remote monitoring, and digital platforms—were recommended. Furthermore, during the National Water Council meeting addressing the upcoming National Water Plan (2025–2035), which will come into effect following its publication in the Official Gazette, it was emphasized that the promotion of smart water management, digital monitoring systems, automation and remote-control applications, as well as precision irrigation techniques, would be prioritized. In this context, the deployment of IoT-based sensors, Geographic Information Systems (GIS), and AI-supported decision support mechanisms has been targeted (Ministry of Agriculture and Forestry, 2025).

Sustainable Water Management and Technology

All approaches adopted in sustainable water management require the use of technology to varying degrees (Table 4.1). An examination of these approaches indicates that the essential technologies needed can be categorized into remote sensing, sensors, digital data processing (AI)) and modelling. Beyond these advanced technologies, water harvesting methods are gaining increasing importance; particularly in the face of climate-change-induced droughts, irregular precipitation patterns, and rising water demand, they serve as alternative and complementary resources with strategic value. Practices such as rainwater harvesting, greywater recycling, and atmospheric water harvesting, when integrated with modern monitoring and decision support systems, become an indispensable component of sustainable water management.

Table 4.1 Technologies in sustainable water management approaches

Approach	Technology examples	References
Agroecology	Soil moisture sensors, remote sensing, yield monitoring, agro-biotechnology	Wezel et al., 2009; Altieri and Nicholls, 2017; Gliessman, 2021
Integrated Water Resources Management (IWRM)	GIS, hydrological models, remote sensing, water quality sensors, decision support systems	Biswas, 2004; Molden, 2007; Loucks and van Beek, 2017; UN-Water, 2021
Precision Agriculture (PA)	GPS, IoT-based irrigation, sensors, satellite imagery, automated irrigation systems, AI-based data analysis	Zhang et al., 2002; Gebbers and Adamchuk, 2010; Mulla, 2013
Sustainable Intensification (SI)	Drip irrigation, low-input optimization, biotechnology, stress-tolerant crop varieties	Pretty, 2008; Tilman et al., 2011; Garnett et al., 2013
Ecosystem-Based Adaptation (EbA)	Remote sensing, ecosystem monitoring, climate modelling, hydrological sensors	Colls et al., 2009; Vignola et al., 2009
Climate-Smart Agriculture (CSA)	IoT-based sensors, mobile applications, remote sensing, water-efficient irrigation technologies, climate-resilient crop varieties	FAO, 2010; Lipper et al., 2014; World Bank, 2015
Water-Energy-Food Nexus (WEF Nexus)	Water-energy-food integration models, databases, energy-water monitoring systems	Hoff, 2011; Ringler et al., 2013
Nature-Based Solutions (NbS)	Rainwater harvesting systems, permeable surfaces, water storage infrastructure, ecosystem services monitoring technologies	Cohen-Shacham et al., 2016; Kabisch et al., 2016

The adoption of sustainable agricultural management strategies that aim to achieve the highest yield without depleting natural resources is particularly encouraged by the FAO and is regarded as a global solution requiring the participation of all countries (Burki, 2022). This approach seeks to reduce the environmental footprint of agricultural production, enhance resource efficiency, and strengthen the resilience of farming systems against climate-related challenges. The principle of sustainability is positioned as one of the core elements of smart farming initiatives that promote the efficient management of water and other agricultural inputs (Velten et al., 2015; Morchid et al., 2024).

The integration of IoT, sensor technologies, remote sensing, and AI into agriculture holds the potential to fundamentally transform cultivation practices (Jung et al., 2023). Through these technologies, researchers and farmers can continuously and accurately analyse variations in environmental conditions that influence crop production, such as precipitation, temperature, wind speed, and soil moisture. Such analyses support decision-making processes in identifying areas that require intervention, monitoring plant health, scheduling planting and harvesting, planning fertilization routines, and notably optimizing irrigation timing (Prakash et al., 2023).

Remote sensing data and GIS techniques play a critical role in monitoring and assessing agricultural areas due to their wide spatial coverage and regular temporal data availability (Allen et al., 2007; Ramírez-Cuesta et al., 2020). Through satellite- and drone-based imaging systems, parameters such as crop health, soil moisture, and water stress can be monitored in real time. These data facilitate accurate determination of irrigation requirements. For instance, by utilizing satellite imagery and sensor data, crop water needs can be precisely identified, and irrigation scheduling can be optimized (Courault et al., 2005).

Ensuring technology-driven efficient irrigation management is only possible through the accurate determination of the amount of water consumed by cultivated areas, namely crop evapotranspiration (ET_c). However, the precise measurement or estimation of ET_c requires the implementation of complex procedures and the use of reliable meteorological data, which significantly complicates the process (Allen et al., 1998; Thorp et al., 2019). Particularly when data acquisition is needed over large-scale agricultural fields, model-based approaches become more advantageous due to the limitations of field measurements (Courault et al., 2005; Senay et al., 2011; Jovanovic and Israel, 2012).

Remote sensing-based ET_c estimation has become a significant research area over the past three decades with the aim of enhancing efficiency in irrigation management. In this context, models such as SEBAL and METRIC have gained wide adoption after being tested under diverse climatic and vegetation conditions (Allen et al., 2005, 2007; Bastiaanssen et al., 2005). In recent years, various user-friendly software tools have been developed to facilitate the integration of these models into agricultural water management practices. These tools aim to reduce error rates through functions such as the analysis of spatially distributed ET maps, multiple simulations, and automated data entry (Steduto et al., 2012; Lorite et al., 2013; Bhattarai and Liu, 2019; Silva et al., 2019). Thanks to advances in computational capacity and algorithm optimization, models like SEBAL and METRIC have become applicable on platforms such as MATLAB (EvaMapper (Atasever et al., 2013)), LandMOD (Bhattarai and Liu, 2019), Python (Hessels et al., 2017), and R (Owusu, 2020).

The monitoring and forecasting of meteorological parameters (temperature, precipitation, solar radiation, wind speed, etc.) render irrigation management a highly complex process. However, data related to these parameters can be automatically measured and modeled through IoT-based devices embedded in the soil. In recent years, innovative IoT edge systems have been developed for irrigation planning in crop production (Zhao et al., 2023). Using various IoT sensors, AI-based solutions for soil moisture measurements have been proposed (Garg et al., 2016; Yu et al., 2021). Among these, the development of wireless sensor networks (WSN), which transmit data via gateways and manage them through cloud computing technologies, has become particularly prominent. These technologies, which collect and analyse agro-environmental data and provide farmers with real-time, actionable decisions, are integrated into management systems that enable accurate timing and quantity determination in irrigation planning. Such approaches vary depending on data collection technology (in-situ sensors and remote sensing), data type, the complexity of agro-hydrological modelling, and the temporal and spatial scale of application (Gubbi et al., 2013; Hamouda et al., 2024). The development and implementation of these technologies, as well as the accessibility of the data obtained, are of great importance for sustainable agricultural management, fostering the exploration of software solutions that provide step-by-step forecasts based on agricultural time series data.

Atmospheric water harvesting, owing to its compatibility with renewable energy sources and its global accessibility, emerges as a promising method for sustainable water management and agricultural production. The atmosphere contains approximately 12.9 tera tons of freshwater (Shiklomanov, 1991; Wahlgren, 2001), which is nearly six times greater than the total volume of all rivers on Earth. This water exists in three main forms—clouds, fog, and vapor—constituting about 10% of the total freshwater resources (Kim et al., 2017). In this context, the efficient harvesting and utilization of atmospheric water is considered a strategy with substantial potential to alleviate water scarcity.

Throughout history, atmospheric water has been regarded as an alternative water source, and various methods for its harvesting have been attempted since ancient times. The condensers constructed in Feodosia on the Crimean Peninsula and the experimental stone condensers developed by Zibold in 1905 represent early applications of this approach (Zibold, 1905; Beysens et al., 2000). However, these examples did not always yield the expected amounts of water, leading to the development of more analytical approaches based on physical processes, pioneered by Monteith (1957). In the following decades, research increasingly focused on methods applicable to arid and semi-arid regions (Gindel, 1965; Klemm et al., 2012; Khalil et al., 2016).

Currently, atmospheric water harvesting technologies are increasingly being shaped within the framework of biomimetic approaches inspired by nature. This approach involves studying natural principles to address technological challenges and adapting these principles into engineering solutions (Pohl and Nachtigall, 2015). In nature, numerous organisms have evolved morphological strategies that enable the sustainable acquisition, use, and storage of water. Notably, the Namib Desert Beetle (*Stenocara gracilipes*) has inspired water harvesting technologies through its morphological adaptations that allow survival under arid conditions. The beetle's cuticle features hydrophilic bumps and hydrophobic troughs, which facilitate the condensation and collection of atmospheric moisture and dew. This unique adaptation has enabled the development of mechanisms with similar surface structures for efficient water collection.

Atmospheric water harvesting systems can serve as a supplementary water source during periods of drought and can be implemented at various scales. For instance, dew harvesting systems provide irrigation water for greenhouses, while fog collection methods enable the provision of potable and irrigation water in coastal and mountainous areas (Tomaszkiewicz et al., 2017; Albornoz et al., 2023).

Furthermore, atmospheric water harvesting systems can be rendered more functional through integration with IoT-based sensor and control technologies (Sukhadeve and Roy, 2016). In these systems, atmospheric parameters such as air temperature, relative humidity, and wind direction and intensity are continuously monitored, and combined with data on soil moisture and crop water requirements to develop irrigation decision support systems. Consequently, the harvested water can be utilized not only in terms of volume but also effectively in terms of timing.

From the perspective of sustainable water management, atmospheric water harvesting can serve as an alternative water source not only in rural areas but also in urban settings for applications such as agricultural production, vertical farming, and irrigation of urban green spaces (Falkenmark et al., 2001; Rockström and Falkenmark, 2015). Moreover, when integrated with management systems, it can contribute to reducing the water footprint and supporting water recovery (Koncagül et al., 2020). Thus, atmospheric water harvesting technologies play a strategic role in sustainable agricultural policies by facilitating the development of climate-resilient farming practices and adaptive irrigation systems.

Conclusion

Effective and sustainable management of water resources within the framework of sustainable agriculture represents a highly challenging objective due to the increasing global food demand and the impacts of climate change. The growing reliance on irrigation in agricultural production exacerbates the degradation of water and soil resources, while irregular rainfall, droughts, and extreme climatic events further complicate water management. In the case of Türkiye, the projected decline of per capita water availability to 1161 m^3/year by 2050, placing the country at risk of becoming water-scarce, underscores the urgent need for multifaceted interventions. International sustainability-focused initiatives and the solution-oriented application of emerging technologies offer hope that integrated approaches can address water management challenges. Within this context, Türkiye's current targets and roadmaps provide a clear direction; however, resilience to potential future water shortages requires strong political commitment, adequate investment, and flexible governance mechanisms. From a technological perspective, innovative solutions such as IoT-based sensors, remote sensing systems, AI-driven decision support systems, and atmospheric water harvesting enhance the precision of irrigation planning and contribute to the efficient use of water. The applicability of these technologies across small- to large-scale farms presents a significant opportunity for sustainable water management. While access to these technologies in Türkiye is not a limiting factor, sufficient institutional collaboration and the transparent sharing of data with the public remain critical. Another key challenge lies in increasing the availability of skilled human resources, which are essential for the effective utilization of these technologies.

In conclusion, sustainable water management can be partially achieved through international initiatives and contemporary technologies. Ensuring the long-term sustainability of this achievement, however, requires not only technological adequacy but also political determination, institutional collaboration, transparent data management, and an increase in qualified personnel. Legal frameworks, incentive policies, and strengthened coordination with local water management authorities are of paramount importance for effective water resource governance. The consistent implementation of Türkiye's current targets and roadmaps within this framework will enable the realization of effective and lasting solutions for sustainable water management.

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