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Innovative Approaches in Agricultural Water Management

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Abstract

Agricultural water management is increasingly recognized as a critical component of sustainable food production under conditions of water scarcity and climate uncertainty. Agriculture is the largest consumer of freshwater globally, yet the sector is under growing pressure from rising temperatures, changing precipitation regimes, groundwater depletion, land degradation, and increasing competition among water-using sectors. These challenges have exposed the limitations of conventional irrigation practices and highlighted the need for more efficient, integrated, and climate-resilient management approaches. This review evaluates the current status of agricultural water management and examines innovative approaches that can enhance water-use efficiency and strengthen the sustainability of agricultural systems. The analysis covers both global and Turkish perspectives and focuses on irrigation modernization, integrated water resources management, basin-scale planning, smart irrigation systems, sensor-based applications, remote sensing, GIS, and data-driven decision support tools. In addition, the study discusses water-use efficiency, water productivity, and water footprint perspectives as key frameworks for evaluating agricultural water performance. Particular attention is given to the implications of climate change, especially increasing drought risk, variability in water availability, and the growing need for adaptation at field, scheme, and basin levels. The review shows that improving agricultural water management requires more than technological innovation alone; it also depends on effective governance, coordinated planning, strong monitoring infrastructure, and adaptive policy frameworks. It is concluded that future agricultural sustainability will depend on the successful integration of technological, institutional, and ecological approaches within a comprehensive water management framework.

Keywords: *Agricultural water management; water scarcity; irrigation modernization; smart irrigation; remote sensing; climate change adaptation*

Introduction

Water is one of the most strategic resources in agriculture because it directly influences crop productivity, production stability, rural livelihoods, and food security. Although agriculture is indispensable for feeding a growing global population, it is also the largest user of freshwater resources, placing the sector at the center of sustainability debates (FAO, 2025; Mancosu et al., 2015). In this context, agricultural water management is no longer only a technical issue related to irrigation delivery. It has become a multidimensional challenge involving resource allocation, ecosystem protection, technological innovation, climate adaptation, and institutional coordination (Ringler et al., 2022; Salem et al., 2022).

The global water crisis has intensified under the combined pressures of population growth, urbanization, environmental degradation, groundwater depletion, and climate change. Recent assessments indicate that agriculture accounts for more than 70 percent of global freshwater withdrawals, while land degradation, declining water quality, and climate variability are increasingly constraining agrifood systems (FAO, 2025; Ingrao et al., 2023). Climate change has further aggravated these pressures by altering precipitation regimes, increasing the frequency of droughts and heat extremes, and reducing the reliability of both surface water and groundwater resources (He & Rosa, 2023; Liu et al., 2022). As a result, future food production must increasingly rely on more efficient, resilient, and knowledge-based water management strategies rather than on additional water abstraction alone.

The Turkish context reflects many of these global challenges. National assessments emphasize that agriculture remains the dominant water-using sector in Türkiye and that growing intersectoral demand, basin-scale imbalances, groundwater pressure, and climate-related risks require more efficient and equitable water management approaches (Presidency of Strategy and Budget of the Republic of Türkiye, 2023a, 2023b; Şeren & Yildirim, 2024). At the same time, the transition from conventional irrigation systems to modern pressurized systems, together with the expansion of digital tools, remote sensing applications, and decision support systems, is creating new opportunities for improving irrigation performance and water productivity (Çetin et al., 2024; Semiz et al., 2025).

Against this background, the aim of this review is to evaluate the current status of agricultural water management and to discuss innovative approaches that can improve water-use efficiency, strengthen climate resilience, and support sustainable agricultural production. The paper focuses on five interconnected dimensions: modernization of irrigation systems, integrated water resources management and basin planning, smart irrigation and sensor-based applications, remote sensing and data-driven decision support tools, and water efficiency and water footprint perspectives. It also examines how climate change is reshaping agricultural water management and why adaptation-oriented strategies are becoming increasingly necessary.

Current Status of Agricultural Water Management

Global patterns of water use

Global agricultural development has historically depended on land and water intensification. FAO (2025) reports that most growth in agricultural production during recent decades has been achieved not through large-scale expansion of agricultural land, but through intensification supported by irrigation, improved varieties, fertilizers, and agronomic management. However, this progress has come with major environmental costs, including water scarcity, land degradation, pollution, and biodiversity loss. Agriculture currently accounts for around 72 percent of global freshwater withdrawals, highlighting the sector's dominant role in water demand and its sensitivity to water stress (FAO, 2025).

This situation is particularly critical in arid and semi-arid regions, where the mismatch between water demand and water availability is becoming more severe. Water scarcity in agriculture is shaped not only by physical shortages, but also by economic, institutional, and infrastructural constraints that limit access to and effective management of water resources (Ingrao et al., 2023). In addition, countries facing increasing water scarcity are often also exposed to food security risks because agricultural production capacity is closely linked to water availability and irrigation reliability (Christoforidou et al., 2023; Mancosu et al., 2015).

Agricultural water use in the world and in Türkiye

Globally, irrigation remains one of the most important drivers of agricultural productivity. According to FAO (2025), irrigated land produces a disproportionately high share of crop output relative to its area, confirming the strategic role of irrigation in food systems. However, future irrigation expansion is increasingly constrained by water scarcity, competition among sectors, ecological limits, and climate change (FAO, 2025; Liu et al., 2022).

In Türkiye, agricultural water use follows a similar pattern but with even greater pressure on the sector. National sources indicate that agriculture uses approximately three-quarters of total water withdrawals in the country, while industry and domestic sectors account for the remainder (Presidency of Strategy and Budget of the Republic of Türkiye, 2023a; Şeren & Yildirim, 2024). This structure makes the efficiency of agricultural water use especially important for national water security. The need for fair allocation among sectors, environmentally compatible planning, and efficient field-level use has therefore become a major policy priority (Babaoğlu et al., 2023; Presidency of Strategy and Budget of the Republic of Türkiye, 2023a).

Another major issue in Türkiye is groundwater pressure. Korkut et al. (2025) show that climate change, population growth, and unsustainable use in agriculture and other sectors have significantly affected groundwater quantity and quality, increasing interest in managed aquifer recharge and other recovery measures. This highlights that agricultural water management cannot be reduced to surface irrigation planning alone; it must also include conjunctive use, recharge strategies, and protection of subsurface water systems.

Current challenges and structural problems

The current challenges in agricultural water management are both physical and institutional. At the physical level, water scarcity, drought, salinization, groundwater depletion, and variable rainfall reduce the reliability of agricultural production (Ingrao et al., 2023; Liu et al., 2022). At the system level, inefficient conveyance, open-channel losses, inappropriate irrigation scheduling, and low field application efficiency continue to reduce effective water use in many schemes (Çetin et al., 2024; Santini et al., 2025).

At the institutional level, fragmented governance, insufficient coordination among agencies, inadequate pricing mechanisms, limited monitoring infrastructure, and weak data integration reduce the effectiveness of water planning and management (Presidency of Strategy and Budget of the Republic of Türkiye, 2023a, 2023b; Salem et al., 2022). In Türkiye, policy analyses also suggest that climate-oriented water planning has often remained reactive rather than fully proactive, which limits long-term adaptation capacity (Babaoğlu et al., 2023).

These conditions show that improving agricultural water management requires more than local technical fixes. It calls for a transition toward integrated, basin-aware, digitally supported, and climate-resilient management approaches that connect irrigation practices with governance, data, and adaptation.

Innovative Approaches in Agricultural Water Management

Transition from conventional practices to modern irrigation systems

One of the most visible dimensions of innovation in agricultural water management is the transition from conventional irrigation practices toward modern irrigation systems. Traditional surface and flood irrigation methods often involve high conveyance and application losses, limited control over water delivery, and lower irrigation efficiency, particularly in water-scarce environments (Rastogi et al., 2024; Santini et al., 2025). In response, modernization has increasingly focused on pressurized irrigation systems such as drip and sprinkler irrigation, improved conveyance infrastructure, volumetric delivery, and better on-farm control.

The benefits of modernization can be substantial. Çetin et al. (2024), in a comparative assessment of two irrigation schemes in Türkiye, found that the modern irrigation scheme showed considerably lower total water use and markedly higher irrigation efficiency, water economic productivity, and farmer income than the older surface-irrigated scheme. Likewise, Hashemi et al. (2024) showed that replacing traditional irrigation with drip systems and combining irrigation improvements with crop and water management measures can significantly reduce unsustainable blue water use and improve sustainability indicators.

However, irrigation modernization should not be treated as a universal solution. Santini et al. (2025) emphasize that while field-scale studies often report clear gains in crop yield and irrigation efficiency after the shift from flood to drip irrigation, basin-scale analyses may reveal trade-offs such as increased consumptive use, reduced return flows, and limited real water savings. This is important because it reminds us that higher efficiency at plot scale does not automatically translate into basin-scale sustainability.

A further nuance is provided by Bouimouass et al. (2022), who show that traditional gravity-fed irrigation systems in some semi-arid settings can support groundwater recharge and preserve water quality with relatively low environmental impact. Therefore, modernization should not be understood as a simple replacement of "old" by "new," but rather as a context-specific redesign of irrigation practices in line with local hydrology, infrastructure, crop patterns, and institutional conditions.

Integrated water resources management and basin-scale planning

Technological change alone is insufficient if it is not embedded in integrated planning and governance. For this reason, integrated water resources management (IWRM) and basin-scale planning have become central approaches in contemporary water policy. Their main premise is that water should be managed not as an isolated irrigation input, but as a shared and limited resource whose allocation affects agriculture, ecosystems, domestic needs, industry, and energy systems (FAO, 2025; Salem et al., 2022).

FAO (2025) stresses that integrated land and water planning is essential where land and water are scarce and where competing societal objectives create trade-offs. Similarly, Ak and Benson (2022), in their comparative analysis of the Konya Closed Basin in Türkiye and the Kern County Subbasin in California, show that water security outcomes are closely linked to actor participation, institutional coherence, and inter-agency collaboration. Their findings suggest that effective basin management depends not only on hydrological conditions but also on how rules structure participation and cooperation.

Baccour et al. (2024) further demonstrate that integrated analysis at basin scale can help identify options that simultaneously improve stream flows, water security, biodiversity, and climate risk reduction. This is especially important under climate change, because sectoral decisions taken in isolation may shift risk from one group of users or ecosystems to another.

In Türkiye, basin-oriented water management has become increasingly prominent in national policy discourse. The *Water Management Specialization Commission Report* and the *Specialization Commission Report on the Management of Soil and Water Resources in Agriculture* emphasize the importance of river basin planning, sectoral water allocation, coordinated management institutions, and climate-sensitive planning frameworks (Presidency of Strategy and Budget of the Republic of Türkiye, 2023a, 2023b). This direction is appropriate, because the success of innovative agricultural water management depends on aligning farm-level practices with basin-scale realities and institutional coordination.

Smart irrigation systems, automation, and sensor-based irrigation management

A major shift in recent years has been the emergence of smart irrigation systems that combine sensors, automation, cloud platforms, and real-time analytics to optimize irrigation decisions. Rather than relying on fixed calendars or farmer intuition alone, these systems use soil moisture, temperature, humidity, weather, and crop condition data to determine when and how much water should be applied (Alharbi et al., 2024; Waqas et al., 2025).

Morchid et al. (2025) present a low-cost IoT-based irrigation system integrated with fuzzy logic and cloud computing, showing that such systems can reduce water losses and maintain soil moisture near a target threshold more effectively than conventional approaches. Similarly, Araújo et al. (2023) propose a cloud-based decision support methodology that integrates data acquisition, predictive analysis, and run-time reasoning. In their case study, the data-driven system reduced water consumption while increasing crop production.

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The value of smart irrigation lies in its ability to make irrigation management more precise, timely, and adaptive. Soil moisture sensors improve irrigation scheduling, automation reduces operational delays, and real-time control makes it possible to respond quickly to water stress or changing climatic conditions (Waqas et al., 2025; Xing & Wang, 2024). These systems are particularly relevant under water scarcity, where over-irrigation and under-irrigation both create serious inefficiencies.

Nevertheless, the diffusion of smart irrigation faces barriers such as upfront investment costs, maintenance requirements, digital literacy limitations, interoperability problems, and unequal access to technical support (Ghosh et al., 2025; Waqas et al., 2025). Therefore, the success of smart irrigation depends not only on engineering performance but also on affordability, usability, farmer training, and institutional support.

Remote sensing, GIS, and data-driven decision support systems

Remote sensing, geographic information systems (GIS), machine learning, and decision support systems have expanded the scale and sophistication of agricultural water management. These tools allow water managers and farmers to move beyond field-by-field observation toward spatially explicit, data-driven, and predictive management.

Rabie et al. (2025) show that remote sensing, GIS, and machine learning together provide a powerful framework for monitoring soil moisture, evapotranspiration, vegetation dynamics, and surface water conditions in arid agricultural regions. Hussain et al. (2025) further highlight that remote sensing can support irrigation scheduling, crop water requirement assessment, water stress detection, and monitoring of water-related problems such as salinity and waterlogging. These tools are particularly valuable where large irrigated areas make direct ground monitoring difficult or costly.

An important operational example is provided by Singh and Das (2022), who developed a remotely sensed water-demand index using soil moisture, NDVI, and thermal information to identify water-stressed agricultural areas at high spatial resolution. Their approach shows that decision-making about irrigation advisories and water allocation can be improved using relatively accessible data without relying on overly complex drought indices.

The strategic importance of these technologies has also been recognized in Turkish policy-oriented documents. The *Specialization Commission Report on the Management of Soil and Water Resources in Agriculture* highlights the use of digital agriculture, satellite systems, and UAV-supported assessments for irrigation and drought-related applications, while the *Water Management Specialization Commission Report* notes that advanced monitoring and modeling systems are promising but depend on robust calibration data and institutional capacity (Presidency of Strategy and Budget of the Republic of Türkiye, 2023a, 2023b). In this sense, the real challenge is not only access to technology, but also the development of data infrastructures, interoperable platforms, and decision processes that can translate information into action.

Water-use efficiency, water productivity, and water footprint perspective

An important conceptual shift in agricultural water management has been the move from focusing only on land productivity toward evaluating performance per unit of water. Water-use efficiency, water productivity, and water footprint approaches reflect this change from “more crop per unit land” to “more value per unit water” (Alharbi et al., 2024; Suna et al., 2023).

Water-use efficiency generally refers to how effectively water is used in crop production, while water productivity emphasizes the quantity or value of output generated per unit of water consumed. Water footprint analysis broadens the perspective by distinguishing among blue, green, and sometimes grey water use and by linking production systems to their wider resource implications (Ingrao et al., 2023; Liu et al., 2022).

Alharbi et al. (2024) show that water-use efficiency can be improved through agronomic and technological strategies such as mulching, canopy management, deficit irrigation, and irrigation modernization. Suna et al. (2023) argue that in water-scarce conditions, the objective should shift from maximizing yield per unit land to maximizing productivity and benefit per unit water, which is exactly the logic behind deficit irrigation and related approaches. Hashemi et al. (2024) integrate crop management and water management strategies and demonstrate that combining modernization with management interventions can reduce unsustainable blue water use and improve overall system sustainability.

The climate dimension is also critical. Liu et al. (2022) show that agricultural water scarcity assessments should include both blue and green water, especially under climate change, because rainfall-dependent systems and soil moisture dynamics are central to future food production. Likewise, He and Rosa (2023) emphasize that improved green water management can significantly reduce production losses associated with climate-driven rainfall insufficiency. These studies indicate that efficiency and productivity indicators should be used alongside broader hydrological perspectives rather than as isolated performance metrics.

Climate Change and Water Management

Climate change is reshaping agricultural water management by increasing drought frequency, altering rainfall patterns, raising temperatures, and amplifying uncertainty in water supply. These changes affect not only total water availability, but also crop water requirements, irrigation timing, groundwater recharge, and the reliability of existing infrastructure (He & Rosa, 2023; Liu et al., 2022).

In rainfed systems, climate change intensifies green water scarcity by reducing the ability of rainfall regimes to meet crop requirements. He and Rosa (2023) estimate that the scale of production losses linked to green water scarcity could increase significantly under warming scenarios, but also show that adaptation measures aimed at retaining more moisture in the soil can reduce those losses. In irrigated systems, rising temperatures and more variable hydrological conditions are likely to increase crop water demand while making water resources less predictable (Liu et al., 2022).

At the regional level, Rastegaripour et al. (2024) show that climate change affects crop patterns and water management decisions by making high-water-consuming crops less attractive under scarcity conditions and by increasing the relevance of modern irrigation methods and better farmer training. In Türkiye, the pressure of climate change on water planning has also been widely recognized in national reports and policy assessments, which emphasize adaptation, early warning systems, efficient use, and more proactive planning frameworks (Babaoğlu et al., 2023; Presidency of Strategy and Budget of the Republic of Türkiye, 2023a, 2023b).

Adaptation strategies therefore need to operate at multiple scales. At the field scale, options include efficient irrigation, deficit irrigation, mulching, crop diversification, and the use of drought-tolerant or climate-smart crops (Kabato et al., 2025; Raza et al., 2025). At the system level, adaptation includes improved monitoring, basin-based planning, managed aquifer recharge, better allocation rules, and resilient infrastructure (Baccour et al., 2024; Korkut et al., 2025). The educational and policy-oriented sources considered in this review also reinforce that climate adaptation in agricultural water management cannot be limited to engineering measures; it must include planning, governance, awareness, and institutional readiness (Konukcu & Göçmen, n.d.; Öztürk, 2019).

Conclusions and Recommendations

Agricultural water management is entering a period in which conventional solutions are no longer sufficient. Growing water scarcity, climate change, ecosystem pressures, and increasing food demand require a transition from fragmented and supply-oriented approaches to integrated, efficient, and adaptive management systems. The literature reviewed in this paper shows that innovation in agricultural water management should not be understood narrowly as the adoption of new devices or irrigation hardware. Rather, it should be seen as a broader transformation involving infrastructure modernization, integrated planning, smart monitoring, data-driven decision-making, and climate-resilient governance.

The review indicates that modern irrigation systems such as drip and sprinkler irrigation can substantially improve field-level efficiency and economic performance, especially when combined with better crop and water management. However, modernization must be evaluated at multiple scales, since farm-level gains do not automatically produce basin-level sustainability. Likewise, smart irrigation, sensors, and automation offer strong potential to reduce waste and improve precision, but their success depends on affordability, technical capacity, and institutional support.

Remote sensing, GIS, machine learning, and decision support systems are increasingly central to future water management because they allow monitoring, forecasting, and allocation decisions to be made more accurately and at larger spatial scales. At the same time, water-use efficiency and water productivity should remain key performance concepts, but they should be interpreted together with blue and green water dynamics and broader water footprint considerations.

Finally, climate change makes adaptation unavoidable. This requires a combination of technical, agronomic, institutional, and policy measures, including efficient irrigation, adaptive crop planning, resilient basin governance, groundwater protection, early warning systems, and data-informed water allocation. In the Turkish context, these priorities are especially relevant because agriculture remains the dominant water-using sector and because national planning increasingly recognizes the need for efficient, coordinated, and climate-sensitive management.

In conclusion, sustainable agricultural water management in the future will depend on the ability to combine technology, governance, planning, and adaptation within a coherent framework. The most successful approaches will be those that improve water productivity, support food security, and protect water resources at the same time.

Declarations

Ethical Approval Certificate

Ethical approval was not required for this study because it is a review paper and did not involve animals, human participants, field experiments, or the collection of primary data..

Author Contribution Statement

Eray Harman: Conceptualization, literature review, investigation, data curation, formal analysis, writing—original draft preparation.

Belgin Çakmak: Conceptualization, methodology, supervision, validation, writing—review and editing.

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Conflict of Interest

The authors declare no conflict of interest.

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