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RECEIVED 20 February 2025

ACCEPTED 01 October 2025

PUBLISHED 03 November 2025

CITATION

Vranešević M, Meseldžija M, Grabić J,
Zemunac R and Boukalova Z (2025)
Irrigation water quality in a framework
of sustainable development goal 6: a review
of challenges impacts policy alignments.
Front. Agron. 7:1580338.
doi: 10.3389/fagro.2025.1580338

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Irrigation water quality in a framework of sustainable development goal 6: a review of challenges impacts policy alignments

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This review article aims to consolidate existing classification systems and evaluate the suitability of irrigation water in the context of Sustainable Development Goal 6 (SDG 6), with particular focus on targets 6.3, 6.4, and 6.5. The review explores key physico-chemical parameters of irrigation water quality and their role in determining water usability. Common classification systems such as FAO and US Salinity Laboratory (USSL) frameworks are examined, alongside their application in assessing impacts on soil health, crop productivity, and ecosystem stability. Findings indicate that inadequate irrigation water quality, particularly due to high salinity and sodium content, leads to soil salinization, reduced yields, and degradation of water and soil resources. These effects also extend to environmental and economic systems, through biodiversity loss and increased production costs. Effective management practices, such as improving drainage, using appropriate irrigation water, and applying soil amendments, are useful to mitigate these adverse effects and maintain soil and plant health. Mitigation strategies to address the economic impacts of unsuitable irrigation water quality include infrastructure investment, educational initiatives and policy enforcement. These strategies are closely aligned with European policy initiatives such as the Water Framework Directive, the European Green Deal, and the Blue Deal, all of which aim to promote sustainable irrigation practices and support the successful implementation of SDG 6 targets. The review emphasizes the practical relevance of these findings for policy-makers, water managers, and agricultural stakeholders seeking to implement sustainable irrigation practices and enhance local water resilience under SDG 6 targets.

KEYWORDS

irrigation, water quality, usability assessment, SDG6, European legislative and missions

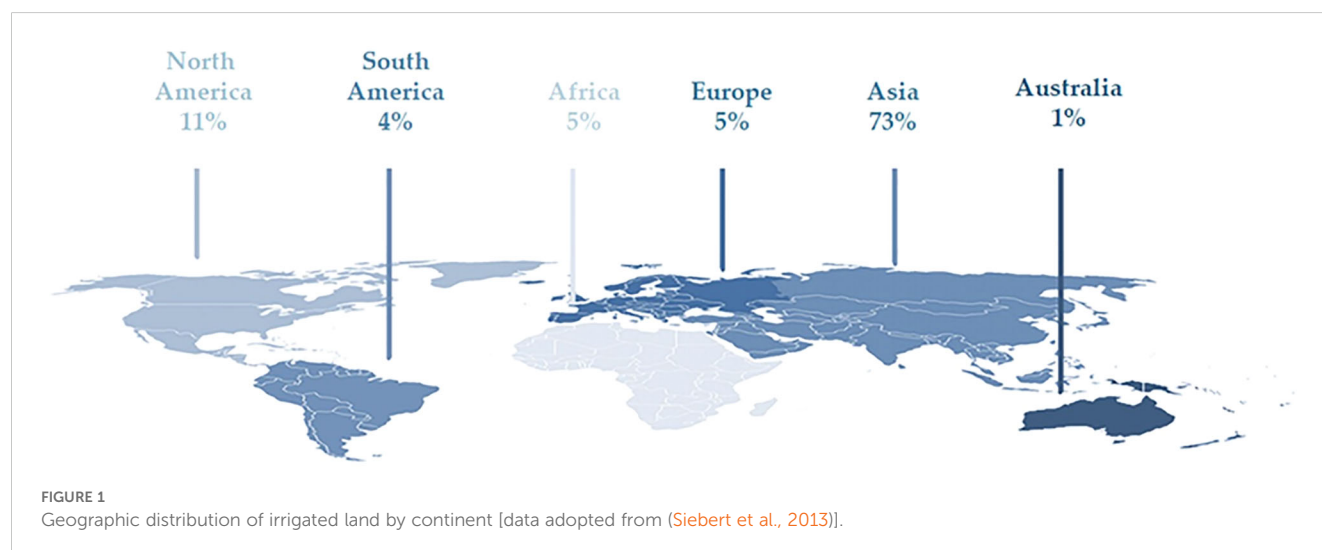
1 Introduction

Population growth has led to greater demand for nutritious and safe food, while also increasing awareness of the need to preserve natural resources such as water, soil, and biodiversity. This growing demand places direct pressure on irrigation systems, increasing the need for reliable water sources, expanding irrigated land, and accelerating the degradation of both water quality and infrastructure. In many regions, limited availability of freshwater leads to competition between domestic, industrial, and agricultural uses, making efficient irrigation practices essential for sustainable food production. These challenges represent a major concern for agriculture and water management, which are already threatened by climate change (Elmahdi, 2024). These irrigation-related challenges must be addressed within a broader global framework that promotes sustainable resource management. In this context, the United Nations adopted the Sustainable Development Goals (SDGs) in 2015, as a set of global objectives to guide actions towards social equity, environmental protection, and economic sustainability by 2030. Among the 17 SDGs, Goal 6 is of particular importance, as it focuses on ensuring water availability, improving quality, and promoting integrated water management issues that are central to the effectiveness and resilience of sustainable irrigation practices.

Consideration of irrigation water quality within SDG 6, which focuses on ensuring the availability and sustainable management of water, is crucial in agriculture, and implementation of sustainable irrigation practices that support the assessment of water quality is essential (Arora and Mishra, 2022). With projected population growth, climate change, and increasing hydrometeorological extremes such as droughts and floods, understanding both water quantity and quality becomes vital for sustainable management (Hfaiedh et al., 2025). Recent studies have emphasized the importance of integrating advanced water treatment technologies and sustainable practices to achieve SDG 6 targets (FAO, 2020; Ho et al., 2020).

Irrigation plays a key role for maintaining food security and economic growth, making it essential to understand the quality of water used for irrigation. Interestingly, on a global scale, there is a vast disparity concerning the representation of irrigated areas. Namely, the most represented irrigated areas are in Asia, making 73%, while in second place is North America with 11% as shown in Figure 1. By analyzing irrigation water quality, it can support efforts to achieve this goal by identifying potential risks to human health and the environment, as well as ensuring optimal crop growth (Perret and Payen, 2020; Gad et al., 2023). Monitoring of hydrochemical indicators (cations, anions, pH, and EC - electrical conductivity) in assessing the quality of irrigation water can provide valuable insights into the suitability of water for agricultural use (Gaagai et al., 2023). For example, high EC indicates elevated salinity, which in arid regions can reduce crop yields by 15–30% due to osmotic stress. Similarly, imbalanced pH can impair nutrient availability, while excessive sodium or chloride ions can degrade soil structure and damage sensitive crops (Vranešević et al., 2024). Throughout the history of mankind, along with advancement of crop production irrigation techniques have been developing (Angelakts et al., 2020). Nowadays, despite the high progress of technology that upgrades even irrigation practices, the fact that these technologies are not available to all farmers, but only to users in some regions, and misapplication of irrigation, still results in significant environmental degradation. For example, salinization caused by improper irrigation affects over 20% of irrigated land worldwide, reducing soil fertility and crop productivity (Rengasamy, 2010; McDermid et al., 2023).

Given these global challenges in irrigation - ranging from unequal access to modern technologies, environmental degradation such as salinization, and uneven distribution of irrigated land—there is a growing need to evaluate and harmonize how irrigation water quality is assessed. This review aims to consolidate prevalent classification systems and assess the suitability of irrigation water in the context of achieving Sustainable Development Goal 6, with particular focus on water quality, efficiency, and integrated resource management.



This review was based on a structured and selective analysis of relevant academic and policy literature. The search was conducted primarily through Scopus, Web of Science, and Google Scholar using combinations of the following keywords: “irrigation water quality,” “SDG 6,” “salinity,” “sodicity,” “agricultural water management,” “European water legislation,” “climate change and irrigation,” and “sustainable irrigation practices”.

The literature included in this review spans from the early 1980s to 2024, with an emphasis on publications after 2020 to capture the most recent developments in science, policy, and SDG implementation. Foundational works published prior to 2000, such as the FAO and USSL classification systems, were included due to their ongoing relevance and widespread application in irrigation water quality assessment.

While a large body of literature was consulted during the writing of this review, only a selection of the most pertinent and high-quality sources has been explicitly cited. The selected studies were categorized thematically and synthesized to identify key challenges, classification frameworks, agricultural and environmental impacts, and policy linkages relevant to Sustainable Development Goal 6.

In addition to reviewing current practices, this article aims to identify key regulatory gaps and suggest integration pathways for SDG 6 within national and European policy frameworks.

2 SDG 6 and irrigation water quality

2.1 Overview of SDG 6

Commonly known as the ‘water goal’, SDG 6 provides a structured framework for achieving water security and plays a crucial role in accomplishing targets of all the SDGs. There are 8 targets under SDG 6 that ensure a fundamental role in achieving availability and sustainable management of water and sanitation for all by 2030. First target is 6.1. titled “Safe and affordable drinking water” and it implies that by 2030, achieve universal and equitable access to safe and affordable drinking water for all. Second target is 6.2. - End open defecation and provide access to sanitation and hygiene. This target suggests that by 2030, it is necessary to achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations. Target 6.3. - Improve water quality, wastewater treatment and safe reuse and it indicates that by 2030, it is necessary to improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally. Target 6.4. - Increase water-use efficiency and ensure freshwater supplies represent a need that by 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity. Fifth target 6.5. - Implement integrated water resources management, indicating that by 2030,

it has to be implemented integrated water resources management at all levels, including through transboundary cooperation as appropriate. Target 6.6. - Protect and restore water-related ecosystems means that by 2020, it has to be protected and restored water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes. Seventh target 6.7 is related to Expansion water and sanitation support to developing countries which implies that by 2030, it has to be expanded international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies. Last target in SDG 6 is target 6.8. - Support local engagement in water and sanitation management. This target implies that there must be some kind of support and strengthen the participation of local communities in improving water and sanitation management ([The global goals, Ensure availability and sustainable management of water and sanitation for all; Secretary-General, 2017; United Nations Environment Programme, 2021](#)).

2.2 Aligning SDG 6 and irrigation water quality

The irrigation water quality is one of the most important in the context of SDG 6, especially in target 6.3., 6.4. and 6.5 ([Germann et al., 2023](#)). Irrigated agriculture plays a key role in global food production, as it provides stable and high yields, which are a priority in agricultural production. Also, the sustainability of this sector depends on the continued availability of high-quality water resources ([Molden et al., 2011](#)).

Surface or underground water, as water sources, are essential for the long-term maintenance of the productivity of irrigated highly profitable agriculture production, for example seed production. Recognizing the seriousness of this issue, water security has been emphasized as a priority for SDG 6, as water resources are unevenly distributed in time and space, causing floods and drought. Flooding usually leads to the contamination of water sources, destruction of used equipment, and destruction of annual production, which results in a significant reduction or complete absence of yield. Droughts result in water scarcity, reduced agricultural productivity, and ecosystem degradation, which also has the same effect as floods. These extreme hydrometeorological phenomena are further intensified by climate change. The availability of freshwater for irrigation is increasingly constrained by increasing demand for food production, and changes in water availability due to climate change.

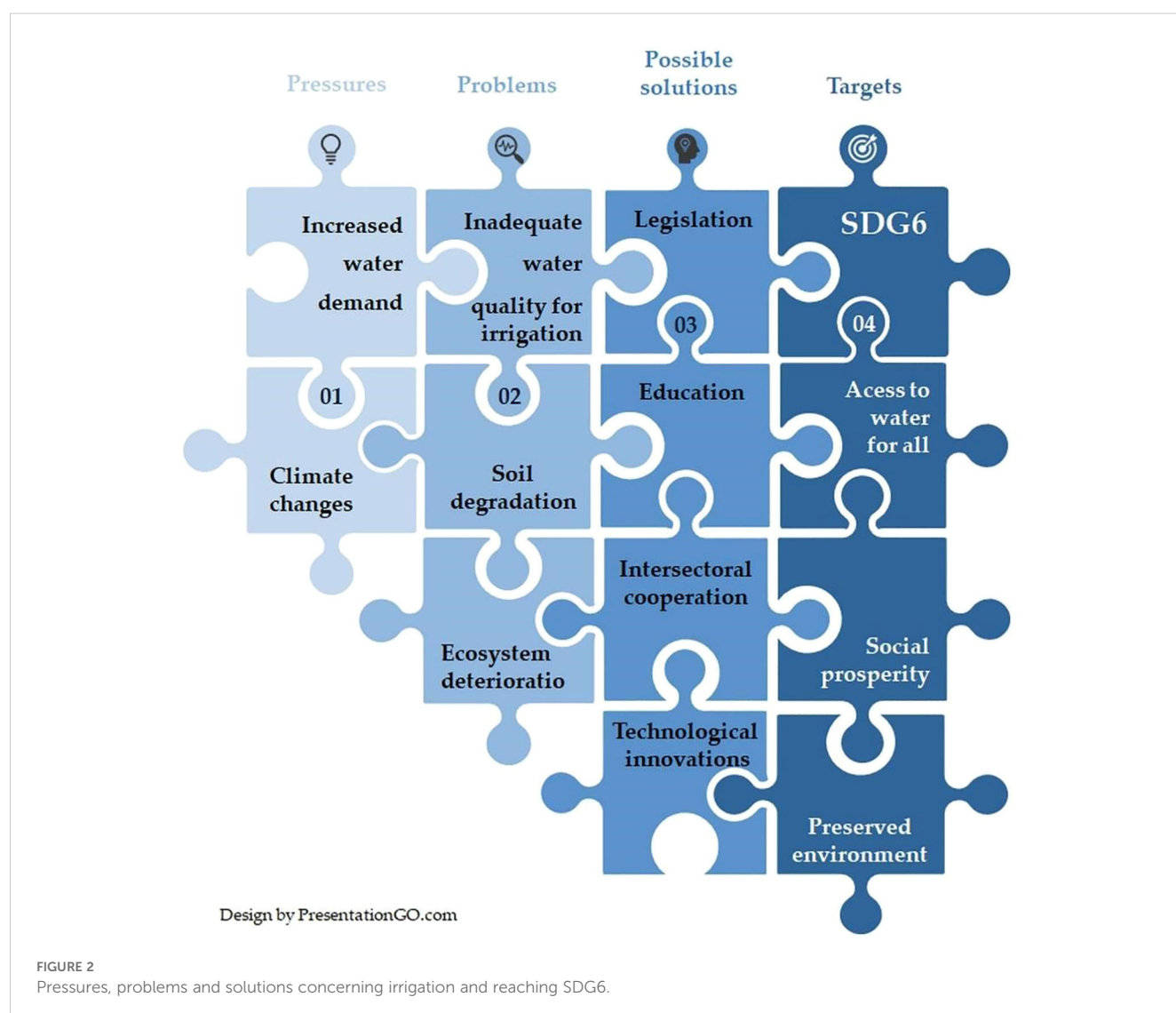
Intensive agricultural production and preservation of natural resources could be in balance by using modern technological models of prediction of precipitation and other meteorological parameters as well as constant monitoring of parameters of water quality which has a direct impact on cultivated crops and soil. One of the strategies for preserving the quantity and quality of water resources for irrigation consists in establishing criteria for the appropriate use in all productive activities ([Behmel et al., 2016](#)). Introducing modern technologies – for example different sensors,

models, and geophysical techniques, which assume soil moisture, hydrological balance and evapotranspiration, significantly reduces and optimizes water consumption. These technological innovations include automated systems based upon coupling sensors and precision irrigation, thus enabling real-time control (Lozoya et al., 2016). Technological innovations such as remote sensing, artificial intelligence (AI), and blockchain offer valuable tools for advancing sustainable irrigation practices. Remote sensing enables precise water mapping and monitoring of crop water needs, contributing to SDG 6.4 by improving water-use efficiency. AI supports predictive modeling for irrigation scheduling and soil moisture forecasting, while blockchain technology ensures transparency and traceability in water allocation and use. These tools collectively support SDG 6.3 (by reducing misuse and pollution), 6.4 (by increasing efficiency), and 6.5 (through better resource governance) (FAO, 2020).

The quality of irrigation water is a main determinant of the overall sustainability of water resources and, by extension, the achievement of SDG6. Water contaminated with pollutants,

excessive nutrients or salts in irrigation water, can have detrimental effects on crop productivity, soil health, irrigation equipment and the overall wellbeing of ecosystems (Delanka-Pedige et al., 2020). The holistic approach emphasizes the interconnectedness of irrigation water quality and other sustainable development goals. This case highlights the need for a comprehensive strategy to address the challenge of consolidating prevailing systems of classification and assessment of suitability of irrigation water in order to achieve SDG 6 (Guerra-Rodríguez et al., 2020). These alignments could be performed as shown in Figure 2.

Parameters such as Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), and Residual Sodium Carbonate (RSC) are directly relevant to SDG 6.3, which aims to improve water quality and reduce pollution. For example, high EC values indicate salinity stress that can lead to secondary soil salinization, decreasing land productivity and increasing the risk of salt leaching into nearby water bodies. Similarly, high SAR levels contribute to sodification and poor soil structure, reducing infiltration and increasing runoff, which may carry pollutants. Monitoring these parameters helps



prevent degradation of both soil and water resources, aligning agricultural irrigation practices with SDG 6.3 goals of reducing contamination, improving treatment, and ensuring safe reuse.

2.3 Definition and importance of irrigation water quality assessment and classifications

2.3.1 Water quality parameters and their importance

Irrigation water quality assessment refers to the systematic evaluation of the chemical, physical, and biological characteristics of water used for irrigation. This assessment involves analyzing parameters such as pH, salinity, electrical conductivity (EC), concentrations of positive and negative ions (e.g., sodium, calcium, magnesium, potassium, chlorides, sulfates and bicarbonates), presence of heavy metals, organic contaminants, and microbial load (Park et al., 2016). The primary goal is to determine the suitability of water for irrigation purposes and to identify potential risks to soil health, crop productivity, irrigation equipment for irrigation and human and environmental health (Khan et al., 2006).

Among these parameters, several indices are widely used to evaluate the specific risks irrigation water poses to soil and crop systems. These include SAR, SSP, RSC, and others, which are explained in more detail below.

SAR represents the relative ratio of Na⁺ ions to Ca²⁺ and Mg²⁺ ions in water. The SAR value expresses the potential of sodium to accumulate in the soil as a result of the continuous use of sodium-laden water (Ayers and Westcot, 1985). Based on the SAR range, irrigation water can be classified into four classes: SAR<10 (excellent), 10–18 (good), 18–26 (doubtful), and SAR>26 (unsuitable).

SSP is a practical index that represents the ratio of sodium and potassium to the sum of the cation concentrations. It serves as a reliable indicator of water suitability for irrigation, with values below 50% considered suitable and those above 50% deemed unsuitable (Guerra-Rodríguez et al., 2020).

RSC represents the amount of sodium carbonate (NaCO₃) and sodium bicarbonate (NaHCO₃) in irrigation water (Eaton, 1950). Soil irrigated by water with a high RSC and presumed high pH value becomes infertile due to NaCO₃ deposition. Excesses of CO₃ and HCO₃ cause the deposition of Ca and Mg, which disturbs the soil structure and can activate Na in the soil. Thus, based on the RSC value, sodium endangerment can be assessed with three degrees: RSC<1.25 (low), 1.25–2.5 (medium), and RSC>2.5 (high).

Soil permeability is affected by the long-term use of irrigation water, the quality of which is reflected in the total content of dissolved salts, sodium content, and bicarbonate content. To integrate these three factors, Doney (1964) presented the permeability index (PI), which evaluates the ability of soil water to move. According to PI values, waters can be classified as follows: class I (>75% - suitable), class II (25–75% - good), and class III (<25% - unsuitable).

Similar to SAR, KR belongs to the group of indicators of the danger of alkalization based on the ratio of the concentration of

Na⁺ to the concentrations of Ca²⁺ and Mg²⁺. Values of KR>1 indicate elevated amounts of sodium in irrigation water and the risk of alkalization, and such water is considered unsuitable for irrigation, while values of KR<1 indicate that the water is suitable for use in irrigation (Kelly, 1963).

The magnesium adsorption ratio (MAR) is an index that determines irrigation water quality regarding magnesium hazard (Szabolcs and Darab, 1964). Higher magnesium values risk agricultural yields after releasing sodium from the soil. Long-term use of water with high concentrations of magnesium negatively affects the chemical structure of the soil and reduces crop yield. Water with a value of MH<50% is considered suitable for irrigation, while water with an MH>50% is considered unsuitable.

Water hardness is the result of the presence of divalent metal cations Ca²⁺ and Mg²⁺. The total hardness can be expressed as the sum of the concentrations of Ca²⁺ and Mg²⁺, which is equivalent to the concentration of CaCO₃.

This indicator evaluates the quality of irrigation water from the aspect of its impact on the functional parts of the irrigation system. TH values around 100 mg/L provide corrosion control and are acceptable limits (Rawat et al., 2018).

In addition to the analysis of individual parameters, irrigation water quality can also be evaluated using a set of related indices. These indices facilitate the assessment of risks associated with sodium accumulation, magnesium hazard, soil permeability, and total water hardness. Table 1 presents the standard formulas used to calculate these indices.

2.3.2 Impacts on soil health

Irrigation water could indicate soil health and fertility since they are foundational elements for sustainable agricultural productivity. Healthy, fertile soils provide essential nutrients, support robust

TABLE 1 Formulas for calculating irrigation water quality indices.

	Criteria	Formulas
	Sodium hazards	
(1)	Sodium absorption ratio SAR	$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})}{2}}}$
(2)	Soluble Sodium percentage SSP	$SSP = \frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \times 100$
(3)	Residual sodium carbonate RSC	$RSC = (HCO_3^- + CO_3^{2-}) - (Ca^{2+} + Mg^{2+})$
(4)	Permeability index PI	$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^+} \times 100$
(5)	Kelly's ratio KR	$KR = \frac{Na^+}{Ca^{2+} + Mg^{2+}}$
	Magnesium hazards	
(6)	Magnesium adsorption ratio MAR	$MAR = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}}$
(7)	Total hardness	$TH = 2,5 \times Ca^{2+} + 4,1 \times Mg^{2+}$

plant growth, and enhance water retention and drainage capabilities. This is important for optimizing water use efficiency, ensuring crop yields, and mitigating environmental impacts (Suvendran et al., 2024). Main indicators of soil health include organic matter content, soil structure, microbial activity, and nutrient availability. In irrigation conditions, soil health is determinative for several reasons such as water retention and drainage, nutrient cycling, and soil structure with stable aggregates. Soil fertility refers to the soil's ability to supply essential nutrients to plants in adequate amounts and proportions indicating a framework of nutrient availability, pH and salinity management, and fertilizer efficiency. Soil health and fertility ensure efficient water and nutrient use, support higher crop yields and better-quality produce during critical growth stages, and ensure resilience to stress (Nikolaou et al., 2020; Zhang et al., 2021). Soils which are rich in organic matter and microbial diversity can suppress diseases and pests, but under irrigation, excess moisture could otherwise promote pathogens.

2.3.3 Equipment considerations

Irrigation equipment may be negatively affected by unsuitable water. Inadequate quality water with high levels of suspended solids or certain chemicals can clog emitters and corrode irrigation systems, leading to increased maintenance costs and reduced efficiency or complete collapse of the irrigation system. Well-planned monitoring and assessment of irrigation water quality are essential to detect and prevent such issues (Kucserka et al., 2023).

2.3.4 Environmental consequences

Environmental sustainability under irrigation conditions could be improved if it takes into account erosion control by using cover crops and reducing potential for surface runoffs. Another positive impact on the environment could be reflected in maintaining soil health through organic matter and conservation practices that enhance carbon sequestration (Kochsiek et al., 2009; Tahat et al., 2020). This contributes to climate change mitigation by reducing greenhouse gas emissions from agricultural lands. By addressing these aspects holistically, agricultural productivity is enhanced, resilience to climate change is promoted, and human and ecosystem health is safeguarded (Karri and Nalluri, 2024).

2.3.5 Classification systems

The goal of all classifications and assessments is to ensure optimal water quality to support healthy plant growth, take into consideration all mentioned risks, while minimizing negative effects which occur in irrigation practice (Malakar et al., 2019; Masoud et al., 2022). The most common classifications in worldwide use are FAO and US Salinity Laboratory classification (USSL). The FAO classification offers a comprehensive analysis of irrigation water quality, addressing critical factors such as salinity, infiltration rates, and ion toxicity. Specifically, it analyzes how salinity impacts crop water availability and how infiltration rates influence water penetration into the soil. Additionally, the FAO classification assesses the toxicity levels of particular ions, especially sodium

(Na⁺) and chloride (Cl⁻). An advantageous feature of this classification is its inclusion of a list of crops categorized based on their sensitivity to these specific ions: sensitive, semi-sensitive, and tolerant (Ayers and Westcot, 1985). Although Ayers and Westcot (1985) remains a widely referenced framework, recent research has expanded upon their criteria to better reflect contemporary irrigation challenges and policy frameworks (Guerra-Rodríguez et al., 2020; Schomberg et al., 2023). The USSL classification analyzes the interaction between salinity and alkalinity, providing insights into their combined effects on irrigation water quality. While traditional classification systems like FAO and USSL provide foundational frameworks, recent research suggests the need for updated criteria that reflect current environmental challenges and policy developments (Guerra-Rodríguez et al., 2020). This classification is an instrument in assessing irrigation water by categorizing it according to the risks of salinization and alkalization, thereby guiding appropriate water management practices (Richards, 1954). Table 2 shows the salinity hazard (C Class) and sodicity hazard (S Class) which are the criteria used to define the classes for evaluating usability.

3 Impacts and challenges of irrigation water quality

3.1 Agricultural productivity

Inadequate irrigation water quality characterized by high levels of dissolved salts and sodium most commonly leads to soil salinization, sodification, waterlogging, and a reduction in crop productivity. These impacts contribute to the long-term degradation of soil and water resources, and result in considerable agronomic challenges.

Salinization is the most typical impact of inadequate quality irrigation water on agricultural soils. Irrigation with high-salinity water leads to the accumulation of soluble salts in the soil profile, particularly in the root zone. This reduces the osmotic potential of the soil solution, limiting plant water uptake and inducing physiological drought conditions. These issues are especially critical in arid and semi-arid regions where evapotranspiration exceeds precipitation, exacerbating salt accumulation (Rengasamy, 2010). According to Singh, to effectively manage soil salinization, it is essential to adopt several integrated practices (Singh, 2017). Using suitable, low-salinity water and implementing efficient irrigation methods, such as drip or subsurface systems, can significantly reduce the accumulation of salts (Gad et al., 2025). Regular leaching with excess water is crucial to remove salts from the root zone, while soil amendments, including organic matter, gypsum or the new approach of biochar, improve soil structure and enhance the leaching process. Selecting salt-tolerant crop varieties and practicing crop rotation can maintain agricultural productivity under saline conditions. Choosing crops based on their salt tolerance is a key component of sustainable irrigation planning. Crop tolerance to salinity is typically expressed in terms of the electrical conductivity of the soil saturation extract (ECe). Table 3

TABLE 2 USSL classification of irrigation water based on salinity (C) and sodicity (S) levels.

CS class	S1	S2	S3	S4
C1	Suitable/good water	Moderate to good	Moderate	Moderate to poor
C2	Moderate to good	Moderate	Moderate to poor	Poor
C3	Moderate	Moderate to poor	Poor	Very poor
C4	Moderate to poor	Poor	Very poor	Unsuitable water

presents examples of commonly cultivated crops and their corresponding salinity tolerance levels.

The installation of comprehensive drainage systems mitigates salt accumulation, and routine soil testing and monitoring enable timely management interventions (Singh, 2017a). Furthermore, the application of mulch helps diminish surface salt accumulation and improves soil moisture retention. Integrating these strategies can effectively mitigate the adverse effects of salinization, preserve soil health, and promote sustainable agricultural practices.

Understanding crop-specific thresholds for salinity tolerance enables farmers and land managers to optimize crop selection and adapt irrigation strategies in areas affected by saline water.

Sodification, another critical soil degradation process, occurs when irrigation water has a high Sodium Adsorption Ratio (SAR). This promotes the replacement of calcium and magnesium ions by sodium ions on soil colloids, causing the dispersion of soil aggregates (Ibrahim et al., 2023). The resulting deterioration of soil structure reduces permeability and aeration, impairs root development, and restricts water and nutrient availability (Qadir and Oster, 2004). To effectively manage sodification, which degrades soil structure due to excessive sodium accumulation, several challenges in practices are essential. The application of gypsum or organic amendments such as compost can displace sodium ions and enhance soil aggregation. Using low-sodium water for irrigation and adopting efficient irrigation systems, can minimize sodium accumulation. Periodic leaching with excess water can remove accumulated salts, although it must be carefully managed to prevent waterlogging. The same as salt affected soil, testing and monitoring are important for detecting sodium levels and adjusting management practices accordingly. As well as selecting salt-tolerant crops, practicing crop rotation, erosion control through mulching and cover cropping, coupled with soil

conservation techniques such as contour plowing, helps protect soil structure and manage sodification effectively (Srivastava, 2020).

Waterlogging is another concern associated with inadequate quality irrigation water and inefficient irrigation systems. Excess water saturation reduces soil porosity and oxygen availability, inhibiting root respiration and growth. Prolonged waterlogging promotes root decay and the activity of anaerobic pathogens, while also leading to nutrient leaching and changes in soil redox potential. These effects ultimately reduce plant vigor and productivity (Barrett-Lennard, 2003). Effective management practices, such as improving drainage, using appropriate irrigation water, and applying soil amendments, are useful to mitigate these adverse effects and maintain soil and plant health (Valipour, 2014). Implementing efficient drainage systems, both surface and subsurface, is critical for removing excess water and preventing its accumulation. Raised beds can enhance root aeration by elevating plant roots above saturated soil levels (Qadir and Oster, 2002; Qadir and Schubert, 2002). Beyond agricultural productivity, the use of inadequate irrigation water also poses serious risks to environmental systems, including soil degradation, water pollution, and biodiversity loss.

3.2 Environmental consequences

Beyond agricultural productivity, the use of unsuitable irrigation water also threatens ecological systems that can be reflected through habitat degradation and biodiversity loss. Elevated concentrations of salts and agrochemicals such as synthetic fertilizers, pesticides, hormones, and growth regulators, can leach into soils and be transported to adjacent water bodies via surface runoff. This leads to the degradation of both terrestrial and aquatic habitats (Begović et al., 2023).

High salinity levels alter soil and water chemistry, rendering environments inhospitable for native species and contributing to biodiversity loss (Rhoades et al., 1992). The presence of toxic elements such as heavy metals (e.g. lead, cadmium, and arsenic) in irrigation water can result in phytotoxicity, impaired plant growth, and death of soil microorganisms and fauna (Eid et al., 2023). These effects cascade through the food web, ultimately affecting wildlife populations (Chaudhry et al., 1998). Additionally, excess sodium leads to soil compaction and reduced infiltration, increasing surface runoff and erosion. Transported sediments and contaminants can smother aquatic vegetation and disrupt benthic habitats, further reducing biodiversity (Smith et al., 1999; Damseth et al., 2024). Another influence on the environment

TABLE 3 Salt tolerance of selected crops (Khan et al., 2006; de Vos et al., 2016).

Crop	Salinity tolerance (ECe dS/m)	Tolerance category
Barley	> 8.0	Tolerant
Cotton	7.0–9.0	Moderately Tolerant
Wheat	6.0–8.0	Moderately Tolerant
Corn (Maize)	~1.7	Moderately Sensitive
Bean	~1.0	Sensitive
Strawberry	< 1.0	Highly Sensitive

could be indicated through exacerbating waterlogging in agricultural areas, creating anaerobic soil conditions that are detrimental to many terrestrial plants and soil organisms. This leads to negative changes in plant production and to shifts in species composition, favoring water-tolerant plants and microbes, and ultimately reducing overall biodiversity (Manik et al., 2019). These environmental effects are closely tied to significant economic consequences, particularly in regions where agriculture is a primary livelihood.

3.3 Economic implications

The economic consequences of using low-quality water for irrigation are substantial. Reduced crop yields and diminished crop quality lower marketability and directly impact farmers' incomes. Inadequate quality irrigation water can result in stunted growth, discoloration, and reduced nutritional value of crops. These products may fail to meet consumer expectations or regulatory standards, especially in competitive markets (Linderhof et al., 2021). To mitigate the adverse effects of poor-quality irrigation water, farmers often need to invest in soil amendments (gypsum, organic matter or biochar) and treatments. This includes applying different amendments to remediate soils, leaching salts with additional water, and using organic or inorganic fertilizers to address nutrient imbalances. These practices increase the cost of production, reducing overall profitability (Srivastava, 2020). In extreme cases, consumers may avoid produce from regions known for inadequate water quality, causing reputational damage and further losses (Lal, 2004). At a broader scale, relying on agricultural exports may encounter trade barriers if produce is found to be contaminated or substandard. International trade regulations can lead to restrictions or bans, affecting national economies and the livelihoods of farming communities (Hoekstra and Hung, 2005; Chapagain et al., 2006). To address the interrelated agricultural, environmental, and economic challenges of inadequate quality irrigation water, a set of targeted mitigation strategies must be implemented.

3.4 Mitigation strategies

To address the multifaceted challenges posed by poor irrigation water quality, an integrated management approach is essential. This includes regular monitoring of water quality parameters and the adoption of best practices tailored to local soil and crop conditions. Key strategies involve using salt-tolerant crop varieties, optimizing irrigation scheduling, and implementing water-efficient technologies like drip and subsurface irrigation systems. Water treatment (e.g., blending or filtration) and the use of chemical and organic soil amendments (e.g., gypsum, compost, or biochar) can correct imbalances and improve soil structure. Infrastructure improvements, such as constructing effective drainage systems and using raised beds, help prevent waterlogging and salinity buildup. Capacity building through farmer education and extension services

ensures that stakeholders are informed and capable of making adaptive decisions to maintain sustainable and productive agricultural systems. These mitigation strategies, when applied consistently, not only protect agricultural productivity but also enhance environmental resilience and support long-term sustainability goals in line with SDG 6.

4 Strategies and legislative for irrigation water quality

4.1 Strategies for mitigating the consequences of using unsuitable irrigation water quality

Mitigation strategies to address the economic impacts of unsuitable irrigation water quality include infrastructure investment, educational initiatives and policy enforcement.

The development and maintenance of infrastructure for efficient water use, including modern irrigation systems and water treatment facilities, can significantly mitigate the adverse effects of poor irrigation water quality. Government subsidies and financial support for farmers to adopt these technologies enhance agricultural productivity and ensure agricultural sustainability (Datta and Dayal, 2000; Styczen et al., 2010). Additionally, educating and training farmers on managing irrigation water quality, applying different soil amendments, and implementing efficient irrigation practices can enhance stable and high quality yields. Extension services and agricultural advisory programs play an important role in disseminating knowledge and technologies that assist farmers in mitigating the adverse effects of poor water quality (FAO, 2017; Rosa et al., 2020; Giordano et al., 2023; Yalin et al., 2023). Implementing policies to regulate water quality and sustainably manage water resources is crucial for protecting agricultural productivity and minimizing economic losses. This includes monitoring and enforcing water quality standards, promoting best practices in irrigation management, and supporting research and development in sustainable agriculture (Gleick et al., 2002; Yalin et al., 2023).

4.2 Irrigation water quality in the context of aligning SDG 6 with European legislative

In the context of aligning SDG 6 with European legislative measures, the significance of irrigation water quality is emphasized in promoting resource efficiency, sustainable agricultural practices, environmental protection, and climate resilience. Several legislative frameworks and initiatives, including EU Missions, the European Green Deal, and the Blue Deal, incorporate water quality considerations within their broader environmental and sustainability objectives. These initiatives collectively aim to ensure the efficient use of water resources, mitigate the impacts of climate change, and protect ecosystems, thereby underscoring the

importance of maintaining high standards of irrigation water quality.

4.2.1 EU missions

EU Missions, as part of Horizon Europe, are ambitious, goal-driven initiatives aimed at addressing major societal challenges. Two key missions relevant to irrigation water quality are the “Restore our ocean and waters” and “Mission on soil health and food” (*EU Mission: Restore our ocean and waters by 2030, Implementation plan*; *EU Mission: Soil deal for Europe, Implementation plan*). These missions underscore the critical role of water and soil management in achieving sustainable agriculture and food security. Ensuring suitable irrigation water is vital for maintaining soil health, preventing salinization, sodification, waterlogging and sustaining productive agricultural systems, has direct consequences in aligning with the mission’s objectives.

4.2.2 European green deal

The European Green Deal is a comprehensive strategy aiming to make Europe the first climate-neutral continent by 2050. It has some basic strategies that are related to irrigation water quality. One of the most important is the Water Framework Directive (WFD) which aims to achieve good qualitative and quantitative status of all water bodies. The WFD stipulates that EU Member States should aim to achieve at least good ecological status or potential and chemical status for all surface water bodies, and chemical status and quantitative status of groundwater. Ecological status/potential of surface waters express the criteria used to assess the quality of the structure and functioning of surface water ecosystems, which are influenced by pollution and habitat degradation. River Basin Management Plans (RBMPs), produced by all European Member States as part of implementing the WFD, would provide a useful window into country freshwater restoration landscapes. Monitoring and improving irrigation water quality are necessary for meeting the WFDs objectives, as agricultural runoff can significantly impact surface and groundwater quality (*Chave, 2001*). The implementation of the European Green Deal and related policies underscores the necessity for sustainable water management practices, as highlighted in recent studies (*Nikolaou et al., 2020*). Another important strategy is Strategy on Adaptation to Climate Change addresses water scarcity and resilience through Building Resilience from climate impacts, especially extreme weather events, and promoting nature-based solutions encouraging the use of natural systems to address climate change impacts (*Strategy on adaptation to climate change*). One more very important strategy is Biodiversity Strategy. The core component of this strategy is protecting and restoring ecosystems, where maintaining good irrigation water quality helps prevent nutrient runoff and contamination of water bodies, thus supporting biodiversity and the health of aquatic and terrestrial ecosystems (*Biodiversity strategy*). Typical agricultural strategy is Farm to Fork Strategy. Focus of this strategy is on creating a fair, healthy, and environmentally-friendly food system. Ensuring high irrigation water quality is fundamental for producing safe, high-quality

food, reducing dependency on chemical inputs, and promoting sustainable farming practices (*Farm to fork strategy*). Further, Circular Economy Action Plan aims to improve water quality by reducing wastewater and microplastic in water (*Circular economy action plan*).

4.2.3 European blue deal

The Blue Deal is a comprehensive set of recommendations for a sustainable water policy for Europe as a strategic priority. The work is based on a set of opinions covering the social, economic, environmental and geopolitical aspects of water as well as water challenges concerning agriculture, industries, infrastructures and sustainable consumption (*Blue deal*). Irrigation water quality could align with the goals of the Blue Deal, through different patterns: Efficient use of irrigation water, free from contaminants, supports water conservation efforts, reduces over-extraction from natural sources, and ensures sustainable water availability; reducing agricultural runoff containing pesticides, fertilizers, and other pollutants, thereby protecting water resources and ecosystems; and ensuring water quality helps farmers adapt to climate changing conditions by maintaining water and soil health and crop productivity. In this way the EU can promote more integrated and effective approaches to water management, benefiting both agricultural practices and environmental health.

4.3 Synergies and implementation

Aligning SDG 6 with European legislative frameworks and initiatives can create synergies for enhancing irrigation water quality through coordinated research funded from diverse sources and the efficient implementation of policies. The EU has many different funding programs that support research and innovation in water quality monitoring systems, sustainable irrigation practices and water treatment technologies. However, certain gaps persist in the implementation of EU water policy, particularly regarding the integration of ecological knowledge and system-based approaches. In past applications of the Water Framework Directive, projects have occasionally relied on trial-and-error methods, lacking strong evidence-based planning. To improve coherence and effectiveness, national frameworks should integrate SDG 6 indicators directly into water, soil, and agricultural monitoring systems. This includes harmonizing data collection, enabling adaptive governance, and improving the traceability between policy goals and operational practices. Regular monitoring of irrigation water quality, coupled with stringent compliance measures, ensures adherence to established standards and guidelines. This is possible only if policies could be implemented Integrated Water Resource Management (IWRM) and Best Management Practices (BMPs). As ecosystems are dynamic and subject to continuous succession and rejuvenation, the impacts of an unsuitable irrigation are likely to change over time. Continuous monitoring to facilitate adaptive management and improve future project designs therefore is important. The communication of insights is essential for progress to be made towards effectively designing and

implementing integrated management of water resources and efficient irrigation systems projects.

The identified policy instruments, including the Water Framework Directive and the Nature Restoration Law, form a foundation upon which practical, science-based solutions can be implemented to achieve SDG 6 (Boon and Raven, 2012). These frameworks are further synthesized in the conclusion to highlight actionable steps forward. Strengthening local governance capacities and fostering stakeholder engagement will be key to ensuring successful translation of these findings into sustainable water use practices at the community level.

5 Conclusions

The growing demand for food and the need to conserve natural resources present major challenges for agriculture and water management, particularly under climate change. SDG 6 emphasizes the importance of access to water and sanitation, making the irrigation water quality a critical factor. This review highlights the impact of inadequate quality irrigation water on soil degradation, crop yield reduction, environmental harm, and economic losses. Key findings of this review include: salinity, sodicity, and waterlogging, all of which impair soil structure and plant productivity.

Classification systems such as FAO and USSL remain essential tools for evaluating water usability, while monitoring indicators like EC, SAR, and RSC enables early interventions. Effective mitigation strategies include infrastructure investments, farmer education, and policy enforcement. However, persistent gaps remain in translating these frameworks into practice.

A significant barrier is the limited adoption of precision irrigation technologies, especially among smallholder farmers. Moreover, policies are often unevenly implemented across governance levels, weakening their effectiveness. Strengthening adaptive management and embedding scientific knowledge into legal instruments, such as the Water Framework Directive and Nature Restoration Law, will be crucial to ensuring SDG 6 targets are met. Addressing these limitations requires not only technological innovation but also stronger policy integration and capacity building at the local and regional levels.

This review goes beyond summarizing current knowledge by identifying critical regulatory gaps and offering concrete recommendations for aligning technical water assessment with actionable policy. In doing so, it bridges science and governance in the context of sustainable irrigation.

Future research should focus on integrating artificial intelligence and remote sensing for real-time water quality monitoring, and on improving governance mechanisms for transboundary water management. Interdisciplinary collaboration among scientists, policymakers, and practitioners will be essential to

address these challenges and implement effective, equitable water strategies across regions.

Author contributions

MV: Writing – original draft. MM: Writing – original draft. JG: Writing – review & editing. RZ: Writing – review & editing. ZB: Writing – review & editing.

Funding

The author(s) declare financial support was received for the research and/or publication of this article. The research in this paper is part of a project entitled: Determination of excess water in Vojvodina within the framework of climate change and extreme hydrometeorological phenomena (contract no. 002955429 2024 09418 003 000 000 001) funded by the Provincial Secretariat for Higher Education and Scientific Research activity). As well of the project: DALIA: Danube Region Water Lighthouse Action (n. 101094070) financed under Topic: HORIZON-MISS-2021-OCEAN-02-02.

Conflict of interest

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