Report on the ICID Question 68:

Non-conventional water (REUSE, desalination): can we really loosen the grip on the resource, and for what uses?

for the 26th ICID Congress to be held in October 2026 at Marseille, France.

General Reporter:

Prof. Juan Antonio Rodríguez Díaz (Universidad de Córdoba, Spain)

Co-Reporter:

Prof. Nicolas Roche (Aix Marseille University, France)

Panel of experts:

Prof. Victoriano Martínez Álvarez (Universidad Politécnica de Cartagena, Spain)

Eng. Ignacio Gómez Lucena (Universidad de Córdoba, Spain)

Prof. Pilar Montesinos Barrios (Universidad de Córdoba, Spain)

Eng. Feras AlMansour (Saudi Irrigation Organization, Saudi Arabia)

Prof. Emilio Camacho Poyato (Universidad de Córdoba, Spain)

Prof. Javier J. Cancela (Universidad de Santiago de Compostela, Spain)

1. Introduction *1*

2. Water REUSE *2*

a. Current use of treated wastewater resources for irrigation at world, European and other key countries levels 2

b. Implications for the hydrological cycle. Direct and indirect use of treated wastewater 3

c. Comparative analysis of regulations for treated wastewater for irrigation at international level. 4

d. Water-Energy nexus and water costs. 6

e. Agronomic benefits. Positive fertilisation effects. Spatial and temporal variability of water quality. 9

f. Main Challenges for implementation 10

g. How can integrated, interdisciplinary, and territorial approaches contribute to overcoming sociological, economic, and regulatory obstacles? 12

3. Desalinated water *14*

a. Current use of treated desalinated water for irrigation at world, European and other key countries levels 14

b. Water-Energy nexus 17

c. Definition of a strategy to specifically meet agricultural needs, both in quantitative and qualitative terms 18

d. Economic model. Desalinated water costs. 20

e. Main challenges for the implementation 21

4. SWOT analysis for the implementation of non-conventional water resources for irrigation. *23*

a. Water Reuse 23

b. Desalination 26

5. Conclusions *29*

6. References *30*

1. Introduction

Global freshwater resources are under unprecedented pressure due to the combined effects of climate change and escalating food demand (United Nations, 2023).

According to FAO AQUASTAT, approximately 307 million hectares are equipped for irrigation worldwide. Total irrigation requirements are estimated at 1,500 km^3, which are met by about 2,673 km^3 of water withdrawn from primary and secondary renewable resources, fossil groundwater, and non-conventional water sources. Agriculture is by far the dominant freshwater consumer globally, accounting for approximately 70% of all freshwater withdrawals and more than 80% of consumptive water use from surface and groundwater bodies. Irrigated agriculture, covering roughly a quarter of the world's cropland, produces about 40% of global food on approximately one-third of harvested land.

The global water balance is further complicated by climate change, which is shifting precipitation patterns, rising evapotranspiration rates, reducing glacier-fed river flows, and increasing the frequency and severity of droughts and floods. Regions already experiencing water stress — including the Mediterranean basin, the Middle East and North Africa (MENA), parts of sub-Saharan Africa, South Asia, and western North America — face the most acute pressures. In semi-arid and arid zones, agriculture critically depends on irrigation, and groundwater overdraft has become the norm. In many basins, extraction systematically exceeds natural recharge rates, depleting aquifers that took millennia to fill. Projections indicate that global food production must increase by 60% by 2050 to sustain the growing population (FAO, 2017), a challenge that countries are already facing in regions like the Mediterranean Basin and North Africa. Per capita water availability has declined from 12,050 m^3/year in 1950 to approximately 7,310 m^3/year in 2000 and is expected to reach just 4,580 m^3/year by 2050, a 62% reduction in a single century, while at the same time total global water consumption is projected to increase by 50% (Ragab, 2023; Shemer et al., 2023).

In response, many nations are integrating non-conventional water sources into their water management schemes, with the reuse of reclaimed wastewater (RWW) and desalinated water (DSW) emerging as central pillars.

However, it is unclear to what extent non-conventional water resources (NCWRs) can help reduce the global water deficit in this uncertain situation. But the key challenge is not purely volumetric but also one of governance, economics, technology deployment, regulatory alignment, and social acceptance, all which shape whether NCWRs can be mobilized at the scale needed to contribute meaningfully to closing the water gap by 2030 and beyond. The following sections analyse the state of knowledge, practice, and emerging strategies for water reuse and desalination in agricultural contexts.

2. Water REUSE

a. Current use of treated wastewater resources for irrigation at world, European and other key countries levels

Currently, an estimated 36 million hectares, roughly 12% of all irrigated land worldwide, use some form of urban wastewater for irrigation. However, only 15% of this reuse occurs within formal, planned schemes where quality and volume are controlled (Ait-Mouheb et al., 2020). Formalizing these practices is essential not only to capture the agronomic benefits of RWW, such as stable supply and nutrient recycling, but also to mitigate the health and environmental risks associated with waterborne pathogens and soil salinization.

Globally, Jones et al. (2021) estimated total global wastewater production at 380 billion m^3/year, of which 63% is collected, and 52% is treated. The formally reused fraction — approximately 40.7 billion m^3/year — is distributed unevenly, with the highest absolute and relative volumes concentrated in a small number of countries. This value represents approximately 22% of all treated wastewater produced.

One of the biggest challenges is the availability of data on water reuse from official sources. It is truly difficult to find reliable data on water reuse and the percentage of that reuse allocated to agriculture for different countries. Globally, China and the United States are the leading producers of reclaimed water. However, when it comes to the percentage of these resources reused, Israel leads the way at approximately 90%. Of this amount, the majority is used for agricultural irrigation. The Middle East and North Africa region, despite its small total wastewater volume, achieves relatively high reuse rates driven by acute water scarcity. Southern European countries (particularly Cyprus, Malta, Spain, Italy, France, and Greece) lead within the EU context. Saudi Arabia considers treated wastewater a strategic resource because renewable freshwater availability is extremely limited. In 2025, Saudi Arabia produced 2.18 billion m^3 of TWW, yet over 27% is being reused in agriculture, industry, and landscaping, with 92% allocated to agriculture, representing 4.7% of total agricultural water use.

Spain is the leading EU country in water reuse by volume, accounting for over half of Europe's reclaimed water production, estimated at around 532 hm^3/year, or 11% of all treated wastewater. The main destination of reclaimed water in Spain is agriculture (72.4%), followed by parks and gardens (17.2%), industrial processes (2.5%), sewer/street cleaning (2.4%), and others (5%) (INE, 2023). The Spanish Mediterranean regions of Murcia (91.4%) and Valencia (42,5%) (INE, 2023; MITECO, 2021) have the most developed reclaimed water use for irrigation under the stricter European regulation 2020/741/EU. The governance structure involves a complex interaction between the national and basin water plans, river basin authorities, urban wastewater utilities (often private operators), and irrigators' associations as end users.

Overall, treated wastewater reuse is increasingly recognised as a reliable alternative water source that supports agricultural sustainability and reduces dependence on freshwater resources.

b. Implications for the hydrological cycle. Direct and indirect use of treated wastewater

The adoption of treated wastewater for agricultural irrigation has important implications for the natural hydrological cycle that are not always adequately considered in project planning or regulatory frameworks. Treated wastewater reuse can occur through both direct and indirect pathways, so it requires a holistic approach that considers interactions among water abstraction, use, return flows, and ecosystem water requirements. A distinction must be made between the following uses:

Direct reuse (DR) of treated wastewater occurs when it is intentionally supplied from treatment plants to users through dedicated transport and distribution networks. This water is intended for end uses such as irrigation, industry, or groundwater recharge via controlled infrastructure. It involves applying reclaimed water directly to crops via surface, sprinkler, or drip irrigation systems. The water that infiltrates the soil and is not consumed by evapotranspiration eventually recharges local and regional aquifers, contributing to baseflow in rivers and streams. When reclaimed water replaces a freshwater source that was previously discharged to a river or aquifer, the net hydrological effect depends on whether the original freshwater abstraction is reduced.

Indirect Reuse (IR) occurs when treated wastewater is discharged into natural systems such as rivers or aquifers and later reused downstream or extracted from wells, where water quality varies due to mixing and environmental conditions. It is the dominant mode of water reuse globally. When urban or agricultural wastewater is treated to secondary level and then discharged into rivers, lakes, or coastal waters, downstream irrigation districts and ecosystems draw on what is essentially highly diluted reclaimed water. In many river basins, a substantial fraction of natural river flow during low-flow periods is in fact treated wastewater effluent. This indirect reuse is sometimes unplanned and unregulated, raising questions about cumulative pharmaceutical loading, nutrient enrichment, microplastics, and antibiotic resistance genes in receiving water bodies (Macedo et al., 2022).

Managed aquifer recharge (MAR) using reclaimed water represents a planned form of indirect reuse that offers multiple benefits: it improves reclaimed water quality through soil-aquifer treatment (SAT), provides a buffer against seasonal variability, and contributes to groundwater replenishment. MAR with reclaimed water for surface and groundwater recharge can enable indirect potable reuse while generating quantifiable economic benefits. However, SAT may not fully remove all contaminants of emerging concern (CECs), including N-nitrosodimethylamine (NDMA) precursors, pharmaceuticals, and some

antibiotic resistance genes (Yuan et al., 2017; Declerq et al., 2017). Moreover, monitoring pesticide and herbicide residues is essential to ensure the safe direct or indirect reuse of reclaimed wastewater.

The direct and indirect reuse of treated wastewater has important implications for the hydrological cycle, especially in arid and semi-arid regions where freshwater resources are limited. This reduces withdrawals from rivers, reservoirs, and groundwater aquifers, thereby helping conserve natural freshwater resources and improving long-term water security. Wastewater reuse also augments river flows, replenishes groundwater, and supports ecosystems during dry periods. In many regions, treated wastewater has become an important component of the overall water balance and a reliable non-conventional water source. Wastewater reuse can also influence the hydrological cycle in several ways. Continuous reuse may alter natural flow regimes and reduce the volume of freshwater reaching downstream ecosystems. A critical but often neglected dimension is the reduction of ecological flows when wastewater effluent, which was previously the dominant flow during dry seasons, is diverted for reuse. In semi-arid Mediterranean rivers, treated effluent discharges can constitute the only perennial flow, supporting riparian ecosystems and downstream wetlands. Redirecting this water for irrigation without compensatory measures can have severe ecological consequences, a trade-off that integrated water management frameworks must explicitly resolve.

In agricultural areas, excessive irrigation with treated wastewater may lead to soil salinity, nutrient accumulation, or deterioration of groundwater quality if not properly managed. There is also concern regarding the persistence of emerging contaminants, pathogens, and trace chemicals that may not be fully removed during treatment.

c. Comparative analysis of regulations for treated wastewater for irrigation at international level

The following section compares different regulatory approaches to the use of reclaimed water and their resulting economic implications, which vary depending on the country in which they are applied.

Risk management approaches: hazards vs. risks

The underlying risk management approach fundamentally shapes the design of water reuse policies. At this point, a clear distinction between the terms "hazard" and "risk" should be made. A hazard is any physical, chemical, or biological agent with the potential to cause harm. In contrast, risk refers to the likelihood that a hazard will cause harm within a specified timeframe, including the severity of the consequences (International Organization for Standardization [ISO], 2018; European Food Safety Authority, 2016). When aiming to minimize health risks in agricultural water reuse schemes, policies

may focus either on improving water quality by reducing pathogen concentrations through treatment (hazard-based approach), or on limiting human exposure to pathogens present in RWW by assessing and managing exposure pathways (risk-based approach).

The hazard-based approach

The hazard-based approach, exemplified by the California Water Recycling Criteria (California State Water Resources Control Board, 2000), prioritizes eliminating harmful agents at the source. These policies are characterized by "end-of-pipe" compliance, where safety is verified through prescriptive treatment requirements—such as mandatory filtration and disinfection—and rigid quality thresholds.

The primary advantages of this approach are its simplicity of enforcement and its ability to build public trust. By adhering to a binary "pass/fail" logic, these regulations offer clear benchmarks for water utilities. However, this rigidity often leads to "one-size-fits-all" standards that do not account for the specific exposure levels of different agricultural practices, which may be unnecessarily conservative and drive-up treatment costs without a proportional increase in safety (Barlow et al., 2015).

The risk-based approach

In contrast, the risk-based approach, advocated by the World Health Organization Guidelines (WHO, 2006), focuses on managing human exposure rather than strictly improving water quality. This paradigm is based on the "fit-for-purpose" and "multi-barrier" strategies, where safety is achieved through a combination of treatment and field-level interventions. Barriers may include specific irrigation methods (e.g., subsurface drip), buffer zones, or mandatory harvest intervals that allow for the natural die-off of pathogens.

While risk-based models are technically flexible and economically attractive for regions with limited infrastructure, they impose a heavy administrative and governance burden, which makes them difficult to enforce via regulations. Verifying compliance in these schemes is decentralized; it requires monitoring the behaviour of numerous individual farmers rather than the outlet of a single treatment plant. Furthermore, these models can face social hurdles such as the "yuck factor", as consumers may perceive the water as less safe if it does not undergo intensive, centralized treatment (Savchenko et al., 2019).

The hybrid model

Recognizing the trade-offs of the previous models, recent international milestones such as the Regulation (EU) 2020/741 (European Parliament & Council of the European Union, 2020) and ISO 16075 (ISO, 2020) have adopted a hybrid approach. This model bridges the gap by combining mandatory hazard-based quality benchmarks—to ensure public confidence—with site-specific risk management strategies (e.g., implementing multiple barriers and adapting the quality requirements of RWW to its intended use) that incorporate risk-based flexibility (Maffettone & Gawlik, 2022). Under the EU framework, for instance,

RWW must meet minimum quality requirements, but its use is further governed by a Risk Management Plan that identifies additional site-specific hazards and required barriers. In fact, the implementation of effective barriers enables the use of less intensively treated RWW. The hybrid approach aims to reconcile the stringent safety requirements needed for public trust with the operational pragmatism required for farmer adoption.

Economic implications

Ultimately, the economic sustainability of agricultural water reuse is linked to the chosen regulatory framework. While hazard-based policies provide a clear, treatment-driven safety margin that simplifies compliance through centralized monitoring, their high capital and energy requirements can create a prohibitive financial barrier for small-scale projects lacking economies of scale. Conversely, the operational flexibility of risk-based models often comes at the cost of significantly higher governance and field inspection expenses to ensure distributed barriers remain effective.

As highlighted by Expósito et al. (2024), the disproportionate cost burden on small reuse schemes—nearly double that of large projects—demonstrates that rigid, "one-size-fits-all" standards may inadvertently hamper the use of RWW in decentralized contexts. Therefore, achieving the goals of a circular water economy requires a sophisticated regulatory balance: implementing standards that are stringent enough to safeguard public health and the environment while remaining flexible enough to be economically viable across diverse project scales. In this context, the emergence of hybrid models represents a critical evolution, offering a pathway to reconcile the treatment-driven safety required for public trust with the pragmatic, site-specific management needed for widespread agricultural adoption.

d. Water-Energy nexus and water costs

The relationship between water and energy is particularly complex in the context of wastewater treatment and reuse. Wastewater treatment plants (WWTPs) are major energy consumers: in Europe, WWTPs account for approximately 1% of total national electricity consumption in most developed countries, with energy intensity varying widely from approximately 0.3 to 1.5 kWh/m^3 depending on treatment level, plant size, and technology. For reclaimed water to meet Class A quality under EU 2020/741, the tertiary treatment steps (typically including sand filtration, membrane ultrafiltration, UV disinfection, and sometimes advanced oxidation processes) add additional energy loads. The energy balance of water reuse must also account for conveyance energy, that is, the energy needed to pump and distribute reclaimed water from treatment plants to irrigated fields. On the other hand, larger plants tend to be more energy-intensive but achieve lower energy consumption per m3 due to economies of scale, while smaller rural plants may be less energy-intensive but face higher unit costs (Rodríguez et al., 2019).

The water-energy relationship in WWTPs is not purely one-directional: some plants can recover energy through anaerobic digestion of sewage sludge to produce biogas, which can be used to generate heat and electricity, meeting a significant percentage of the plant's internal energy demand. Membrane bioreactor technology, as evaluated in Granada (Spain) for agricultural reuse of reclaimed water, can simultaneously meet Class A water quality requirements and produce biogas and biostabilised sludge as additional resources within a circular economy framework (Antiñolo et al., 2022).

The economics of water reuse are complex and highly context-dependent, influenced by the required treatment level, the distance and elevation difference between the plant and the irrigated area, the nature of the receiving infrastructure, and the opportunity cost of the displaced freshwater source. A robust economic assessment must consider both direct costs (capital investment in treatment upgrades, storage, and distribution infrastructure) and indirect costs and benefits (health risk management, fertiliser substitution, reduced pressure on conventional sources, environmental services).

A French cost-benefit analysis of two case studies, Clermont-Ferrand (agricultural irrigation reuse) and Cannes (indirect potable reuse via MAR), found that when full social and environmental benefits are monetised, including reduced environmental discharge, avoided freshwater abstraction, and fertiliser substitution, treated wastewater reuse projects can be economically profitable from a societal perspective even when they appear marginally or non-profitable from a narrow utility perspective. The challenge lies in the appropriate allocation of costs and benefits among the multiple actors involved: municipalities, utilities, farmers, downstream water users, and society at large (Declerq et al., 2020).

For Spain, Table 1 presents an estimation of the unit cost of reclaimed water, depending on the water treatment process used.

Table 1. Unit costs of reclaimed water regarding the treatment process

Reclaiming treatment	Costs	
	Set-up €/m^3	Operating €/m^3
Physical-Chemical + Filtration + Membrane filtration + Residual Chlorine	0.82	0.20
Physical-Chemical + Filtration + Ultraviolet + Residual Chlorine	0.12	0.09
Filtration + Ultraviolet + Residual Chlorine	0.05	0.06
Filtration	0.03	0.06
Physical-Chemical + Filtration + Membrane filtration + Reverse Osmosis+ Residual Chlorine	1.14	0.46
Physical-Chemical + Filtration + Reversible Electrodialysis Residual + Ultraviolet+Residual Chlorine	1.04	0.46

Source: MAPA (2010)

Both reclaiming treatments and the transport and distribution of reclaimed waters involve capital and operating costs. Table 2 shows the figures obtained from the study by Villar-García (2016) where they estimate the capital and operating costs of the production and distribution of reclaimed water in Spain. This study is based on an analysis of projects representing more than 20 % of the total volume of reused water in Spain. It uses the concept of 'annual equivalent cost' (AEC) as a comparative measure between different systems and treatment processes, which allows for the standardisation of both capital costs and annual operating costs. The average cost of production and distribution is around 1.10 €/m^3.

Table 2. Range of unit costs for the production and distribution of reclaimed water in Spain.

	Set-up €/m^3	Operation €/m^3	AEC €/m^3
Reclaimed water production	0.20 – 4.50	0.06 – 0.48	0.08 – 0.84
Reclaimed water distribution	4.00 – 8.00	0.15 – 0.40	0.47 – 1.04
			0.55 – 1.88

Source (Villar-García, 2016)

A study of southeastern Spain found that in greenhouse agriculture, the margin available to absorb increased water costs is substantial, making the premium for reclaimed water (versus conventional groundwater) economically viable (López Serrano et al., 2021). In contrast, for low value rainfed crops, even a modest cost of reclaimed water can be prohibitive without subsidy mechanisms. Policy frameworks should therefore design differentiated tariff structures that reflect value-added by crop type while remaining affordable for small and medium farmers.

e. Agronomic benefits. Positive fertilisation effects. Spatial and temporal variability of water quality

One of the most frequently cited agronomic advantages of treated wastewater for irrigation is its nutrient content. Reclaimed water from secondary and tertiary treatment typically contains substantial concentrations of nitrogen (as ammonium, nitrate, and organic nitrogen), phosphorus, and potassium, as well as micronutrients and organic matter. In many water reuse systems, these nutrients can offset 20–100% of the synthetic fertiliser requirements of irrigated crops, generating both economic savings for farmers and environmental benefits through reduced synthetic fertiliser production (which is energy-intensive) and reduced risk of nutrient runoff from fields over-fertilised with synthetic products (Alcaide et al., 2019; Poustie et al., 2020).

The relationship between reclaimed water nutrient content and agronomic performance must be nuanced. Nitrogen in treated effluent is primarily in ammoniacal (NH_4) and organic forms, which are mineralized to nitrate in soil over days to weeks, providing a slow-release fertilization effect well-suited to perennial crops such as olives, citrus, and vineyards. Gómez Lucena et al. (2024) demonstrated that nitrification processes also occur inside the pipes in collective irrigation water distribution networks and developed a model to predict the water quality that each farmer receives at their hydrant. Studies of olive groves and vineyards irrigated with reclaimed water in southeastern Spain found that soil organic matter increased significantly, bulk density decreased, and the need for supplemental nitrogen fertilisation was substantially reduced compared to plots irrigated with freshwater (De las Heras & Mañas, 2020). Fish farm effluent water, another non-conventional water source, similarly demonstrated a 25% reduction in mineral nitrogen fertiliser requirements for tomato production in Egypt (Abdelraouf et al., 2024).

However, agronomic benefits must be set against the risk of phytotoxic or accumulation effects associated with specific constituents of reclaimed water. Salinity, expressed as electrical conductivity (EC) and, in the context of soil sodicity, as sodium adsorption ratio (SAR), is a major concern. Secondary- and tertiary-treated municipal effluent typically has an EC of 0.8–2.5 dS/m, which is generally acceptable for most crops under well-managed leaching but may lead to salinity buildup in poorly drained soils over time. Xenobiotics

(pharmaceuticals, personal care products, endocrine disruptors, microplastics) are present in reclaimed water at concentrations far below acute phytotoxicity thresholds in most monitored systems. Still, their long-term sub-lethal effects on soil microbiota, crop quality, and human health via food consumption remain areas of active research and regulatory concern (Poustie et al., 2020).

Spatial and temporal variability of reclaimed water quality is a critical management consideration that is often underappreciated in regulatory frameworks and irrigation planning. WWTP effluent quality varies diurnally (reflecting urban activity patterns), seasonally (responding to weather, tourist load, and agricultural chemical discharge), and in response to treatment process disturbances.

Alcaide et al. (2022) proved that changes in N were evident both over time and across an irrigation water distribution network in Southern Spain. Seasonally, N content was reduced during the summer period. Spatially, a clear nitrification occurred from the pumping station to the farms. These variations demonstrate the importance of continuous water quality control to adjust the fertilization plan based on the N content in the water. Also, a comprehensive study of antibiotics, antibiotic-resistant bacteria, and antibiotic resistance genes in a fully reclaimed water distribution system in Spain found significant variations across sampling points and seasons, with bacterial regrowth hotspots identified at storage reservoirs and irrigation emitters. This spatial and temporal variability argues strongly for risk-based management plans that treat the entire water reuse chain as a system, rather than relying solely on effluent quality at the point of WWTP discharge (Cadena-Aponte et al., 2025).

f. Main Challenges for the implementation

The implementation of treated wastewater (TWW) reuse for irrigation faces several major challenges across technical, environmental, economic, social, and institutional dimensions. The principal challenges for expanding safe agricultural water reuse to its potential level are:

High cost of wastewater treatment, infrastructure development, operation, and maintenance: Advanced treatment technologies are often necessary to achieve water quality standards suitable for agricultural irrigation, particularly for food crops, which can place significant financial pressure on governments and water utilities. In many developing regions, limited funding, aging infrastructure, and insufficient technical expertise further constrain the expansion of wastewater reuse systems. Additionally, Energy-intensive treatment and distribution systems may increase operational costs and environmental impacts.

Bridging the treatment-distribution investment gap: Most existing WWTPs in water-scarce regions require significant upgrading to reliably produce high quality water, and the distribution infrastructure to connect them with farms is largely absent.

Environmental and public health concerns also remain significant challenges: Inadequately treated wastewater may contain pathogens, salts, heavy metals, nutrients, pharmaceuticals, microplastics, and other emerging contaminants that can accumulate in soils, groundwater, and crops. Long-term irrigation with reclaimed water may contribute to soil salinity and degradation if monitoring and management practices are insufficient. Ensuring reliable treatment performance, continuous monitoring, and compliance with water quality standards is therefore essential to minimize environmental and health risks.

Institutional and regulatory barriers such as fragmented governance: inconsistent standards, unclear policies, and weak coordination among water, agriculture, and environmental agencies can delay implementation and reduce operational efficiency.

Developing proportionate and evidence-based CEC regulation: The lack of binding limits for pharmaceuticals, microplastics, and antibiotic resistance genes creates both regulatory uncertainty and genuine risks that need to be managed.

Aligning food safety and water reuse regulation: The interaction between water reuse standards and food safety regulations (particularly for exported fresh produce) creates compliance complexity that deters farmers.

Scaling governance and institutional capacity: Many national and sub-national institutions lack the expertise, resources, and mandate to develop and implement the comprehensive risk management frameworks required under regulations such as EU 2020/741.

Building social acceptance: In many countries, farmers and consumers remain hesitant to use reclaimed water because of concerns about food safety, hygiene, and cultural acceptance. Lack of public awareness and limited trust in treatment systems often create resistance to wastewater reuse projects. The "yuck factor" and food market concerns require sustained, evidence-based communication, transparent monitoring, and participatory governance.

Accounting for hydrological feedback: Planning frameworks must explicitly consider the effects of reclaimed water diversion on environmental flows, downstream water users, and aquifer recharge.

Climatic and operational issues also affect the reliability of treated wastewater reuse: Seasonal variations in wastewater generation and agricultural water demand can create mismatches between supply and irrigation requirements.

Addressing climate change impacts on wastewater quality and quantity: Increasing temperatures, droughts, and extreme rainfall events affect both the volume and quality of wastewater generated, requiring adaptive management strategies.

Therefore, successful implementation requires integrated planning, strong regulatory frameworks, public engagement, reliable monitoring systems, and

sustainable financing mechanisms to ensure safe and efficient wastewater reuse for irrigation. Developing holistic strategies to facilitate the adoption of reclaimed water in agriculture is key to its successful implementation, a need highlighted by the SUDOE projects I-ReWater (Huerta et al., 2025) and SOLLAGUA, among others.

g. How can integrated, interdisciplinary, and territorial approaches contribute to overcoming sociological, economic, and regulatory obstacles?

Integrated water resource management (IWRM) frameworks help coordinate urban, agriculture, health, and environmental sectors to ensure that reclaimed water policies, infrastructure, and monitoring systems are aligned with regional water management objectives and sustainability goals. Such coordination improves decision-making, reduces institutional fragmentation, and supports the development of clear regulatory frameworks and water quality standards.

Interdisciplinary approaches are equally important because wastewater reuse challenges extend beyond engineering and water treatment technologies. Collaboration among hydrologists, agronomists, chemists, economists, public health specialists, sociologists, and policy experts allows for a comprehensive assessment of environmental risks, economic feasibility, public health protection, and social acceptance. For example, social scientists can help identify public concerns and cultural barriers related to reclaimed water use, while economists can evaluate cost-benefit scenarios and financing mechanisms that improve project affordability for farmers and governments. Public awareness campaigns and stakeholder engagement programs developed through interdisciplinary cooperation have proven effective in improving trust and acceptance of reclaimed water for agricultural irrigation.

Territorial or place-based approaches further enhance wastewater reuse implementation by adapting solutions to local environmental, economic, and social conditions. Water scarcity levels, agricultural practices, infrastructure capacity, and public perceptions vary significantly between regions; therefore, reuse strategies must be tailored to local contexts rather than applying uniform national models. Territorial planning can support the development of decentralized reuse systems, optimize reclaimed water distribution networks, and identify suitable crops and irrigation methods based on local climatic and soil conditions. In addition, involving local communities, farmers, municipalities, and water users in planning and governance processes increases stakeholder ownership and facilitates regulatory compliance.

The multi-dimensional nature of the barriers to water reuse (spanning hydrology, agronomy, economics, public health, governance, and social psychology) makes integrated, interdisciplinary, and territorial approaches necessary. No single sector or discipline can resolve the challenges in isolation.

A successful strategic plan for the widespread adoption of TWW should consider the following aspects:

Territorial approaches recognise that water reuse viability is fundamentally a function of spatial relationships: between WWTPs and irrigated land, between water quality produced and water quality needed, and between the governance jurisdictions (municipalities, river basin authorities, irrigators' associations) whose cooperation is required to deploy systems at scale. A territorial planning approach that maps WWTP output spatially against irrigation demand, soil types, crop patterns, and groundwater recharge needs can identify priority zones for investment and governance coordination. In Spain, the concurrence of high wastewater production (tourist areas, urban agglomerations) with adjacent intensive horticulture in the Mediterranean fringe (Murcia, Almería, Alicante) creates ideal territorial conditions for integrated reuse systems, but this requires formal coordination mechanisms between urban water utilities and irrigators' associations (Rodríguez Villanueva & Sauri, 2021; Ventura et al., 2019).

Interdisciplinary research and innovation are required to develop the technical, economic, and social knowledge base for safe reuse expansion. This includes: (i) advancing sensor technologies and real-time monitoring for pathogen and CEC detection; (ii) developing cost-effective tertiary treatment technologies suitable for small and medium WWTPs; (iii) creating quantitative economic models that capture the full suite of social and environmental costs and benefits; (iv) advancing QMRA for site-specific risk management; and (v) applying social science methods to understand risk perception, information gaps, and effective communication strategies (Radini et al., 2021; Carter et al., 2024).

Governance innovation: The EU 2020/741 Regulation's requirement for Water Reuse Risk Management Plans (WRRMPs) that span the entire chain from WWTP to irrigated field creates an institutional mechanism for multi-actor coordination. However, the Regulation's implementation requires active facilitation at the national and regional levels, including the designation of a competent authority, support for small utilities to develop required risk assessments, and the creation of market mechanisms (e.g., tradable reuse certificates, risk insurance) that can reduce financial barriers (Berbel et al., 2023).

Stakeholder engagement and co-design: Building farmer and consumer trust in reclaimed water requires proactive communication grounded in genuine participation, not just information provision. Successful reuse programs — in Israel, California, Spain — share a common feature: farmers and irrigation communities were involved in the design and governance of reuse systems from an early stage, giving them ownership of safety protocols and economic benefits. Serious games, citizen science monitoring, and digital platforms that make water quality data transparent and accessible to all stakeholders have demonstrated positive effects on social acceptance (Radini et al., 2021).

Circular economy policy frameworks: The transition from a linear to a circular model of water management — in which wastewater is conceptualised as a resource carrying water, nutrients, and energy, rather than a waste to be

disposed of — provides the conceptual foundation for policy and investment alignment. Circular economy strategies at international, national, and regional level must explicitly include water reuse as a co-delivery mechanism for achieving SDG 6 (clean water), SDG 12 (responsible consumption and production), and SDG 2 (zero hunger) (Fernandes & Cunha Marques, 2023; Berbel et al., 2023).

Financial and economic instruments: Several policy instruments have demonstrated effectiveness in overcoming economic barriers: (i) capital subsidies for treatment and distribution infrastructure (as in Israel and Spain); (ii) differentiated water pricing that cross-subsidises reclaimed water production from urban water tariffs; (iii) nitrogen and phosphorus credits that monetise the fertiliser substitution value of reclaimed water; and (iv) green bonds and public-private partnership structures that mobilise private capital for reuse infrastructure (Declerq et al., 2020).

3. Desalinated water

a. Current use of treated desalinated water for irrigation at world, European and other key countries levels

At the outset, desalinated seawater (DSW) was primarily used to meet domestic and industrial water demands worldwide. However, continuous technological improvements and declining production costs have progressively expanded its application to other sectors, particularly agriculture. Over the last two decades, large-scale DSW supply has emerged as a promising alternative for sustaining irrigated agriculture in water-scarce Mediterranean regions characterized by efficient irrigation systems and high-value crops, such as south-eastern Spain, Israel, and Morocco, as well as in insular contexts lacking freshwater resources, including the Canary Islands (Maki et al., 2025; Martínez-Alvarez and Maestre-Valero, 2025). Other countries where agricultural DSW use remains more limited include Italy, Cyprus, Kuwait, Saudi Arabia, Bahrain, Qatar, Oman, and the United States. At the same time, its potential adoption is being actively explored in regions such as Egypt, Tunisia, Chile, Mexico, and Australia, a trend expected to intensify in the near future (Martínez-Alvarez et al., 2018; Suwaileh et al., 2020). The main experiences of irrigation with DSW are outlined below.

In south-eastern Spain, agriculture has historically faced persistent water scarcity, which has intensified over time. During the mid-1990s, farmers responded to a prolonged drought by installing more than 200 brackish-water desalination plants at the farm scale. Continued water deficits, together with the need to sustain high-value agriculture and reduce groundwater overexploitation, led the Spanish government to launch the AGUA Program in 2004. This initiative focused on constructing or upgrading 29 seawater desalination plants along the Mediterranean coast to support agricultural,

urban, and tourist demands, with an overall production target of 693 Mm^3/year, of which 200 Mm^3/year were allocated to irrigation (Martínez-Alvarez et al., 2017). Most facilities were based on reverse osmosis technology, in some cases incorporating double-pass systems to reduce boron concentrations for agricultural supplies. Currently, approximately 25% of total DSW production in Spain is used for irrigation, a proportion that rises to about 70% in the south-eastern region, where nine desalination plants supply water fully or partially for agricultural purposes (Figure 1).

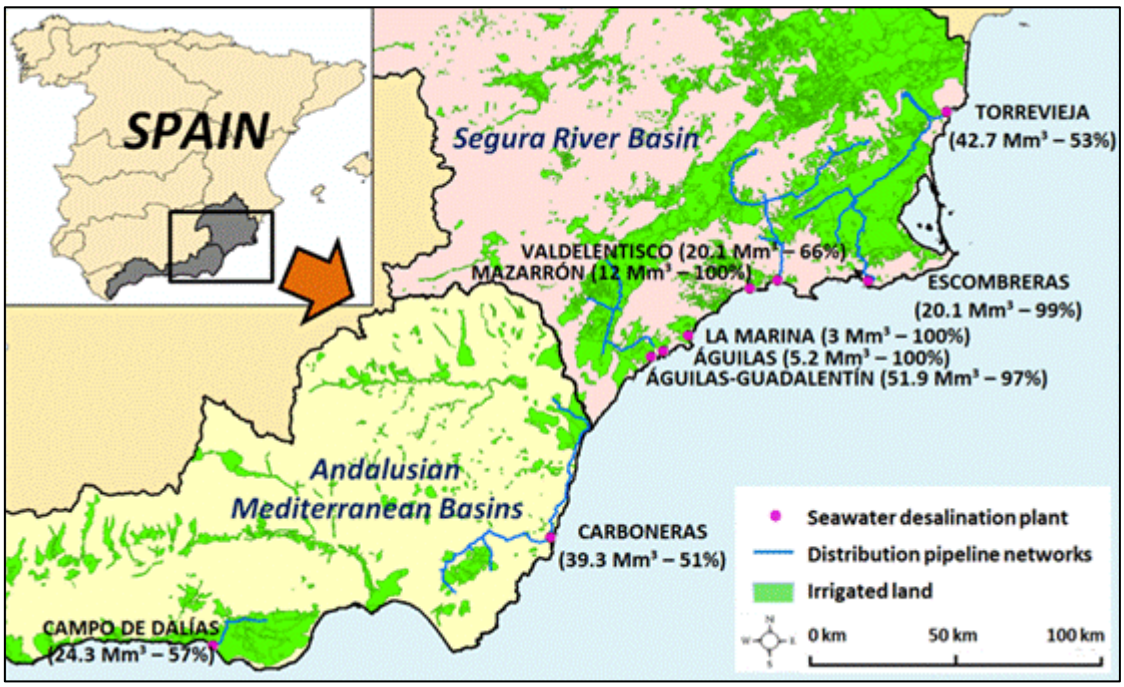


Figure 1. DSW production for irrigation in south-eastern Spain. The figures show the total production and the percentage of agricultural supply at each SWDP. Source: Gallego-Elvira et al. (2021).

In Israel, chronic water scarcity has long encouraged the use of brackish groundwater and reclaimed water for irrigation. Since 2006, DSW has become an increasingly viable alternative. The Israeli Desalination Master Plan, conceived in 1997, aimed to meet domestic water demand by expanding existing facilities and constructing new large-scale desalination plants, ultimately reaching a production capacity of 750 Mm^3/year, with around 200 Mm^3/year intended for agriculture (Spiritos and Lipchin, 2013). At present, five large-scale reverse osmosis plants are in operation, with agricultural use concentrated mainly in southern regions where lower population density allows greater allocation of desalinated water to farming, particularly from the Ashkelon and Palmachim plants (Fig. 2). Their early experimental applications of DSW in irrigation highlighted several agronomic and environmental challenges that must be addressed when integrating this resource into agricultural systems (Ben-Gal et al., 2009; Yermiyahu et al., 2007).



Figure 2. Location and capacity of desalination plants in Israel. The agricultural supply concentrates on southern plants. Source: Martínez Alvarez et al. (2018).

In Morocco, seawater desalination is already supporting agriculture, especially in arid coastal regions such as Souss-Massa, where export-oriented, high-value crops dominate. A representative case is the Agadir desalination plant, which supplies approximately 40 Mm³/year for irrigation and currently serves between 10,000 and 15,000 hectares of farmland devoted to greenhouse vegetables, citrus, and other horticultural products. Nationwide, around 16 desalination plants produce roughly 350 Mm³/year, with an increasing share allocated to agriculture, contributing to the stabilization of production in drought-prone areas and alleviating pressure on overexploited aquifers (Boutagayout et al., 2025). Looking ahead, Morocco aims to expand its desalination capacity to about 1,700 Mm³/year by 2030, with approximately 30% directed—either directly or indirectly through reuse—toward agriculture, alongside plans to develop up to 100,000 hectares of new irrigated land associated with desalination (Jones et al., 2019).

b. Water-Energy nexus

From the water–energy nexus perspective, DSW is characterised by the high energy demand associated with both its production and its subsequent transport to irrigated areas (Zolghadr-Asli et al., 2023). Although reverse osmosis currently represents the most energy-efficient desalination technology in operation, it still requires substantially more energy than conventional water sources, thereby intensifying the water–energy nexus. In south-eastern Spain, total energy consumption for DSW supply is typically between four and ten times higher than that of alternative resources (Martin-Gorriz et al., 2014). Specifically, energy requirements in seawater desalination plants range from 2.77 to 4.10 kWh/m³ for production, with an additional 0.50 to 1.13 kWh/m³ needed for conveyance to irrigation areas (Martínez-Alvarez et al., 2019). Figure 3 shows characteristic values of the specific energy consumption for the different stages of DSW production and supply for irrigation in south-eastern Spain.

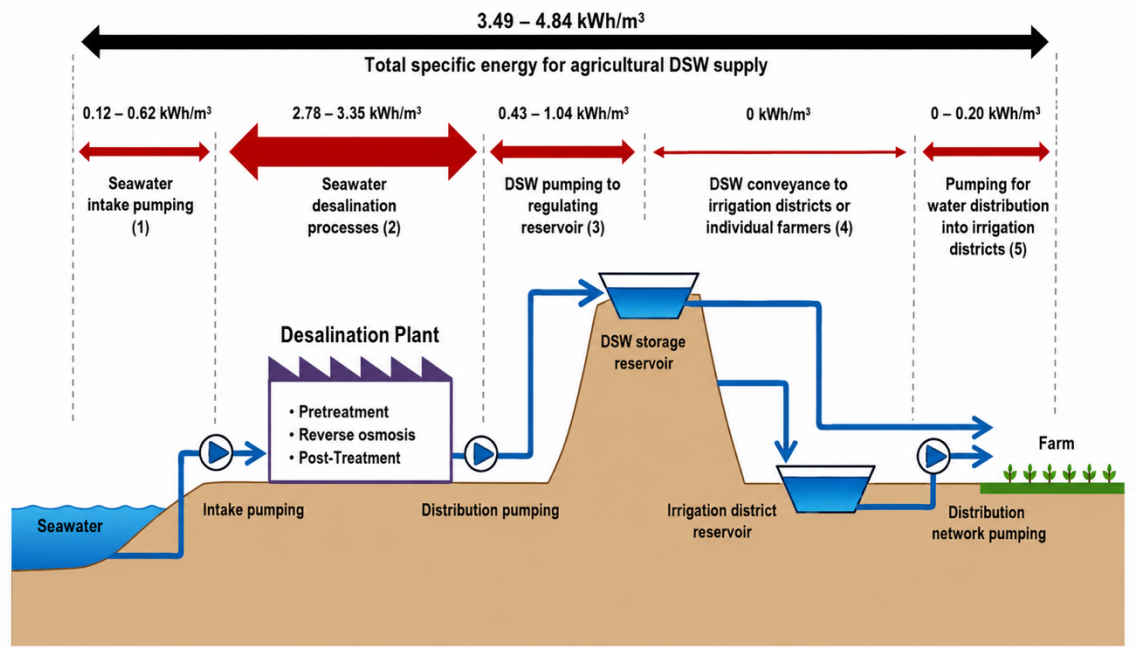


Figure 3. Specific energy for the different stages of DSW production and supply for irrigation in south-eastern Spain. Source: Martínez-Alvarez *et al.* (2019).

Recent desalination plants can achieve specific energy consumption values as low as 1.8–2.2 kWh/m³ for the reverse osmosis stage; however, operational facilities generally exhibit higher values due to the need for extensive pre- and post-treatment processes (Wang et al., 2025). Energy demands may be further increased in agricultural applications, where additional treatment—such as a second reverse osmosis pass—is often required to reduce boron concentrations to levels suitable for sensitive crops, adding approximately 0.50–0.77 kWh/m³ (Shaffer et al., 2012). In Israel, large-scale desalination plants supplying irrigation report values between 2.9 and 3.85 kWh/m³ (Spiritos and Lipchin, 2013),

comparable to those observed in south-eastern Spain when considering intake and desalination stages (Fig. 3). These relatively moderate figures reflect the large capacity and recent commissioning of such facilities, which incorporate advanced membrane technologies and energy recovery systems. Technical factors, including feedwater salinity, target water quality, brine disposal systems, plant capacity, energy recovery efficiency, and membrane type mainly drive variability among plants. Additionally, water distribution at irrigation district and farm scales entails further energy inputs, averaging 0.16 and 0.17 kWh/m^3, respectively, in south-eastern Spain (Soto-García et al, 2013).

The substitution of conventional water sources with DSW in irrigated agriculture would therefore significantly increase overall energy consumption, raising important environmental concerns due to associated greenhouse gas (GHG) emissions. The magnitude of these emissions largely depends on each country's electricity mix, but in all cases, higher energy use may shift irrigated agriculture from a net carbon sink to a net emitter, thereby conflicting with climate change mitigation objectives (Martínez Alvarez et al., 2023). Consequently, assessing GHG emissions associated with desalination is essential to evaluating the sustainability of DSW-based irrigated agriculture.

The apparent maladaptation to climate change is closely linked to the carbon intensity of current electricity systems. A progressive transition toward renewable energy sources would substantially alleviate the water–energy nexus and mitigate the carbon footprint associated with the use of desalinated water in agriculture. In this context, recent studies indicate that desalination plants powered by renewable energy could reduce GHG emissions by up to 90%, significantly improving the environmental performance of DSW-dependent irrigation (Shahabi et al., 2014).

c. Definition of a strategy to specifically meet agricultural needs, both in quantitative and qualitative terms

Irrigation with DSW can be framed within two overarching supply scenarios that determine both its agronomic behaviour and its economic feasibility. The first corresponds to situations in which DSW constitutes the sole or principal water source for irrigation. The second refers to mixed-supply systems, in which DSW is combined with other conventional or non-conventional resources. In the first case, if agricultural requirements are not adequately considered at the design stage of seawater desalination plants, farmers may be exposed to a continuous supply of low-mineral water, which can induce agronomic imbalances, including nutrient depletion and soil chemistry imbalances. In the second case, water quality is inherently variable with seasonal availability and blending ratios among sources, leading to fluctuating physicochemical conditions that require adaptive irrigation and fertigation management. In both scenarios, technical measures can mitigate adverse effects, but they generally

transfer part of the responsibility—and additional costs for fertilisation and soil management—to the farmer.

From a strategic perspective, blending water resources is consistently recommended for both agronomic stability and economic optimization. This includes the mixing of conventional and non-conventional sources, such as surface water, groundwater, reclaimed water (REUSE), or even drainage flows, under controlled conditions. Blending helps buffer water quality variability, reduce phytotoxicity risks, and improve nutrient balance, while simultaneously lowering the effective cost of irrigation water. At present, full reliance on seawater desalination remains largely limited to high-value crops with sufficient economic returns; consequently, blending emerges as the most practical on-farm strategy to broaden its applicability across a broader range of agricultural systems.

Within this framework, a key distinction must be made between new irrigation developments and existing irrigated areas. In new irrigated systems designed around DSW, a detailed pre-assessment of local soil characteristics, crop requirements, and long-term impacts is essential before implementation. This includes evaluating soil salinity dynamics, nutrient management strategies, and the potential need for soil amendments, rootstock selection, or even the introduction of new crop varieties. In such cases, crop selection becomes central, with high-value horticultural species—typically those generating revenues above 2 €/m^3 and with relatively low water requirements—being the most viable option. Nevertheless, further research is still required to assess the feasibility of extending DSW irrigation to strategic staple crops such as cereals and fodder. In contrast, in existing irrigated areas DSW plays a fundamentally complementary role, enhancing resilience against increasing water scarcity driven by rising demand and climate change. Here, desalination acts as a stabilising resource that supports established farming systems.

A further distinction concerns the mode of delivery, which can be either direct or indirect. Direct supply refers to the distribution of DSW from plants directly to irrigation networks. In contrast, indirect supply involves its initial allocation to urban uses, followed by regeneration and subsequent reuse in agriculture. In both cases, water quality management remains critical, particularly when integrating sources with contrasting physicochemical characteristics, as farmers must adapt fertigation strategies to maintain crop productivity and soil fertility.

Finally, environmental and system-level considerations reinforce the need for integrated planning. Proper siting, dimensioning, monitoring, and regulation of desalination infrastructure, together with robust intake and discharge design, are essential to minimise ecological impacts. At the same time, a transition towards circular-economy approaches—such as brine valorisation and membrane recycling—may transform part of the environmental burden into local economic opportunities.

d. Economic model. Desalinated water costs

Because of its high energy requirements, agricultural DSW supply is considerably more expensive than conventional water sources and is therefore priced significantly higher, which often limits its acceptance among farmers (Aznar-Sánchez et al., 2021). These elevated prices can substantially increase crop production costs and, in some cases, jeopardize the economic viability of farms where DSW is the primary or sole water source (Martínez-Alvarez et al., 2023).

The total cost of DSW is highly site-specific and depends on multiple factors, including plant capacity, labour costs, energy sources, land availability, feedwater salinity, and technological development. Overall costs are commonly divided into capital expenditure—associated with the initial investment in seawater desalination plants—and operational and maintenance costs incurred throughout their lifetime. In general terms, these components represent approximately 40% and 60% of total costs, respectively (Lapuente, 2012). However, operational costs are particularly dynamic, as they are largely driven by energy prices, which are inherently volatile, leading to significant fluctuations in the final cost of DSW. Moreover, total costs increase disproportionately when desalination plants operate below full capacity (Ghaffour et al., 2015).

Martinez Alvarez et al. (2019) reported that, at the time of analysis, total reported costs for desalination plants supplying agriculture ranged between 0.50 and 0.66 €/m³ in Israel and between 0.55 and 0.69 €/m³ in south-eastern Spain. The final cost borne by farmers is even higher due to additional conveyance and distribution expenses, particularly when irrigation areas are located inland or at higher elevations. In south-eastern Spain, these supplementary costs include water transfer from the plants to the irrigation districts (0.04–0.06 €/m³), collective management and allocation within irrigation communities (0.03–0.06 €/m³), and on-farm application costs under localised irrigation systems (approximately 0.02 €/ m³) (Soto-García et al., 2013). At the time of analysis, the prices paid by farmers closely reflected this full cost structure, including applicable fees and taxes, in line with the cost-recovery principle established in the EU Water Framework Directive.

Nevertheless, tensions in global energy markets during 2022–2023 led to a marked increase in the cost of DSW for irrigation, reaching nearly 1 €/m³ in Spain, thereby highlighting the strong sensitivity of desalination economics to energy price volatility. This sudden rise generated significant opposition from farmers and prompted the Spanish government to introduce temporary subsidies, partially relaxing the cost-recovery principle. As a result, recent subsidised DSW prices for irrigation have been maintained in the range of 0.35 to 0.50 €/m³ (Orden Ministerial TED/157/2023).

Figure 4 illustrates the evolution of supply prices for large-scale desalination plants worldwide over the past two decades, showing a clear downward trend

from values exceeding 1 $/m³ around the year 2000 to approximately 0.5–0.6 $/m³ in recent years. These values are broadly consistent with those observed in Spain and Israel for agricultural DSW production under stable energy market conditions.

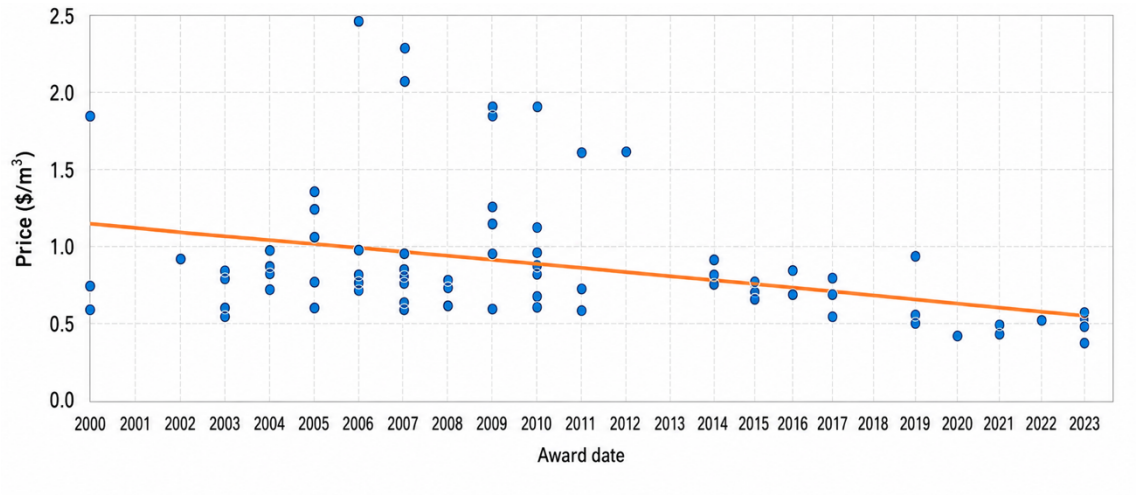


Figure 4. Evolution of DSW price from 2000 to 2023. Source GWI (2023).

e. Main challenges for the implementation

Technical aspects

Early global experiences with DSW for agriculture consistently highlight its high energy demand, which translates into elevated crop production costs and increased GHG emissions. Reverse osmosis has become the dominant mature technology for seawater desalination, supported by two decades of cost reductions in equipment and operational processes driven by large-scale deployment and energy recovery strategies. Efficiency improvements have reduced specific energy consumption to approximately 3–4 kWh/m³, including intake, pre-treatment, and post-treatment stages, although the potential for further reductions is now relatively limited. Energy planning is therefore central to agricultural DSW deployment, not only in terms of plant design but also regarding the upstream electricity generation mix and transmission infrastructure (Spiritos and Lipchin, 2013).

Economies of scale play a significant role in DSW supply, as larger plants generally achieve lower unit production costs. However, these facilities are not always compatible with dispersed or small-scale agricultural systems, where extensive distribution networks—pumping stations, pipelines, and associated energy use—become necessary. Consequently, increasing distance and elevation between production sites and irrigated areas significantly raise costs and can compromise project viability (Daghari et al., 2022).

Finally, a key technical aspect of agricultural DSW supply is the reduction of boron concentration. In addition to conventional reverse osmosis, additional

treatments such as a second reverse osmosis pass or ion-exchange resins selective for boron are often required to meet crop sensitivity thresholds. These solutions improve water quality but increase both capital and operational costs.

Economic aspects

Cost remains the principal barrier to the widespread adoption of DSW in agriculture, particularly for open-field crops such as Mediterranean horticulture and fruit orchards, as well as for inland irrigated systems where delivery costs further increase already high production prices. As a result, current agricultural DSW use is largely restricted to high-value crops, which can absorb the significantly higher water costs associated with DSW (Maki et al., 2025).

The substitution of traditional water supplies with DSW generally reduces farm profitability and, in some cases, may render production economically unviable, exceeding the financial capacity of many agricultural systems (Martínez-Alvarez et al., 2023). Even with recent cost reductions and optimistic future projections, prices around 0.4-0.5 €/m^3 remain challenging for most farmers globally. Although blending desalinated water with other sources can reduce costs, the resulting price typically remains above conventional irrigation water tariffs.

Agronomic aspects

From an agronomic perspective, the chemical composition of DSW introduces several constraints that must be carefully managed to avoid adverse effects on soil and crop productivity (Yermiyahu et al., 2007). Key concerns include the effects of salinity on yield, increased leaching requirements and associated irrigation demand, altered fertilizer requirements due to nutrient composition, boron toxicity risks, and soil alkalinization driven by imbalances between monovalent and divalent cations (Martínez Alvarez et al., 2023).

Post-treatment quality adjustments are therefore often necessary. Increasing calcium and magnesium concentrations helps balance the sodium content of desalinated water, reducing risks of soil sodicity and nutrient deficiencies. Boron removal is particularly critical, as concentrations of 0.7–1.2 mg L^{-1}—common in single-pass reverse osmosis systems—can cause phytotoxicity in sensitive crops such as citrus. In addition, maintaining adequate buffering capacity is essential for stabilizing pH and preventing scaling processes in distribution and fertigation systems (Lahav and Brinhack, 2007).

These agronomic risks can also be partially mitigated through blending DSW with other water sources before irrigation. Nevertheless, establishing formal water quality standards is essential to ensure the physicochemical suitability of the DSW supplied. Such regulation is critical to long-term agricultural sustainability and should be explicitly incorporated into supply contracts for irrigation use.

Environmental aspects

The environmental assessment of desalination for agriculture requires a holistic perspective, as impacts can be both negative and positive (Elimelech and Phillip, 2011). On the negative side, the high energy intensity of desalination contributes to increased GHG emissions, particularly in electricity systems still dominated by fossil fuels. This reinforces the environmental footprint of water supply compared with conventional sources.

Brine disposal is another key concern, particularly in semi-enclosed or shallow marine environments such as the Persian Gulf, where cumulative discharges from multiple plants may lead to ecological degradation. Although engineering solutions such as diffusers and controlled outfalls can mitigate local impacts, the concentration of multiple desalination facilities in restricted coastal areas increases long-term environmental risks (Maki et al., 2025).

On the positive side, desalination can reduce pressure on overexploited freshwater systems, including preventing degradation of aquifers. Overall, environmental impacts depend strongly on-site selection, plant design, regulatory frameworks, and monitoring practices. When properly managed, combining careful environmental assessment with sound engineering design can significantly reduce adverse effects on marine and terrestrial ecosystems.

4. SWOT analysis for the implementation of non-conventional water resources for irrigation

a. Water Reuse

Strengths

Nutrient-rich resource: Reclaimed water provides nitrogen, phosphorus, potassium, and organic matter that partially replace synthetic fertilisers, reducing production costs and environmental loading from excess fertiliser application (Pustie et al., 2020; Alcaide et al., 2019).

Proximity to demand: In most urban and peri-urban contexts, WWTPs are sited near human settlements, which are also often close to agricultural areas, reducing distribution distances and costs compared to long-distance freshwater transfers.

Year-round availability: Unlike surface water (highly seasonal) or rainfall (episodic), treated wastewater flows are relatively constant throughout the year, providing reliability of supply that is essential for perennial crops and intensive horticulture.

Climate resilience: The availability of reclaimed water is largely decoupled from precipitation variability, making it a climate-resilient water source for agriculture in drought-prone regions.

Progressive regulatory framework: In the case of the European Union, EU 2020/741 provides a clear, harmonised minimum regulatory standard across the EU, providing market certainty and positive investment signals for the water sector.

Circular economy contribution: Water reuse exemplifies the circular economy principle by keeping water (and its embedded nutrients and energy) in productive use rather than discharging it as waste (Fernandes & Cunha Marques, 2023; Johannes et al., 2024).

Proven technology: Treatment technologies (MBR, UV disinfection, ozonation, advanced oxidation) capable of meeting the most stringent reuse standards are commercially available and technically mature (Antiñolo Bermúdez et al, 2022; Ho et al., 2024).

Lower energy than desalination: For most applications and source-to-farm distances, the energy cost of reclaimed water production and delivery is lower than seawater desalination (Crutchik & Campos, 2021)

Weaknesses

Inconsistent quality and temporal variability: WWTP effluent quality fluctuates with treatment process performance, influent variability, seasonal loads (tourism, agriculture, weather), and distribution system conditions, creating management challenges (Alcaide et al., 2022).

Salinity and sodicity risks: Long-term irrigation with reclaimed water can lead to salinity accumulation and sodicity development in soils, especially in low-rainfall regions with limited leaching (Poustie et al., 2020).

Presence of CECs: Pharmaceuticals, microplastics, antibiotic resistance genes, and endocrine disruptors in reclaimed water are not fully regulated or routinely monitored, creating residual risks and market acceptance concerns (Berbel et al., 2023).

Infrastructure investment requirements: Upgrading/building WWTPs and building water distribution networks from WWTPs to farms requires substantial capital that may not be recoverable from water tariffs in the short to medium term (Marcantonio et al., 2025).

Lack of social acceptance: Consumer and farmer resistance to products irrigated with treated wastewater is a major non-technical barrier that is difficult to overcome through information alone (Michetti et al., 2019).

Volume limitations: The total volume of reclaimed water available is capped by urban wastewater production. In many rural or peri-urban areas, wastewater volumes may be insufficient to meet large-scale irrigation demand.

Governance complexity: Multi-actor governance involving water utilities, municipalities, river basin authorities, farmers, food safety agencies, and public health bodies creates coordination challenges and transaction costs (Rodríguez Villanueva & Sauri, 2021).

Inland uses: Water authorities often impose restrictions on water reuse in inland areas located far from the coast, where downstream users rely on the same water resources.

Opportunities

Climate change-driven demand for alternatives water resources: Accelerating water scarcity driven by climate change is increasing the economic and policy attractiveness of reclaimed water as a reliable supplement (Ragab, 2023).

Digital technology: Real-time sensor networks, IoT, digital twins, and AI-based process control offer opportunities to improve treatment reliability, reduce costs, and enhance traceability of water quality throughout the reuse chain (Radini et al., 2021).

Nutrient recovery synergies: The co-production of reclaimed water, biogas, and nutrient-rich biosolids from integrated WWTP systems creates multiple revenue streams that can improve the economics of water reuse projects (Antoñolo Bermúdez et al., 2022).

EU Green Deal and Circular Economy Action Plan: EU policy frameworks explicitly support investment in water reuse as part of the circular economy transition, with potential for financing through structural funds, Horizon Europe, and the European Fund for Strategic Investments.

Agricultural policy integration (CAP reform): The Common Agricultural Policy's shift toward conditionality on environmental and resource efficiency performance could incentivise adoption of reclaimed water in water-scarce EU Member States.

Emerging markets: Rapid urbanisation in the MENA, South and Southeast Asia, and sub-Saharan Africa creates new markets for low-cost water reuse technology adapted to local conditions and regulatory environments.

Threats

Regulatory uncertainty around CECs: The absence of clear regulatory limits for CECs at EU and international level creates market uncertainty and potential future liability for farmers and utilities using reclaimed water (Berbel et al., 2023).

Food safety market exclusion: Retailers' refusal to accept products from farms irrigated with reclaimed water, export markets, or food safety certification bodies could undermine the agricultural business case for reuse, even where water quality technically meets standards.

Competition with conventional sources: In seasons or years of high natural water availability, the marginal value of reclaimed waterfalls, undermining the economics of dedicated treatment and distribution infrastructure that requires baseload use to be cost-effective.

Climate change impacts on wastewater quality: Higher temperatures, altered flow patterns, and increased chemical loading from agricultural runoff

during extreme events can degrade WWTP effluent quality in ways that challenge treatment systems.

Public opposition: High-profile contamination incidents — even if attributable to lapses in a single system — can undermine public trust in reclaimed water across the sector, triggering regulatory tightening or market rejection.

b. Desalination

Strengths

Unlimited source water: Seawater is in principle inexhaustible as a freshwater source for coastal regions, providing complete independence from precipitation and hydrological variability (Shemer et al, 2023).

High and consistent water quality: Sea Water Reverse Osmosis (SWRO) produces water with very low TDS (< 500 mg/L), free of pathogens, and of consistent quality regardless of season or upstream conditions, providing a reliable, high-quality agricultural input for sensitive crops.

Proven and scalable technology: SWRO is commercially mature, bankable, and available at scales from a few hundred m^3/day to millions of m^3/day, with a global supply chain for membranes, pumps, and energy recovery devices.

Falling costs and energy consumption: The cost trajectory of SWRO, in the largest modern plants, continues downward as renewable energy, membrane technology, and economies of scale improve (Kurihara, 2021).

Renewable energy integration: Solar and wind-powered desalination can produce freshwater with minimal carbon footprint (0.14–0.19 kg CO_2/m^3), aligning with climate neutrality objectives (Shemer et al., 2023).

Weaknesses

High energy consumption and cost: Despite improvements, SWRO remains more energy-intensive (3.5–4.5 kWh/m^3) and costly than most conventional water supply or wastewater reuse options (Politano et al., 2024).

Economic constraints are also critical, as desalinated water remains significantly more expensive than conventional sources. This limits its use mainly to high-value crops (mainly fruit and vegetables) and often requires subsidies to ensure viability.

Brine disposal challenges: The production of a concentrated brine stream poses environmental risks to marine ecosystems (in coastal discharge) or severe management challenges (for inland Brine Water Reverse Osmosis, BWRO, plants).

Coastal location dependency: SWRO is only economically viable near coastlines or near saline water bodies; serving inland agricultural areas requires long-distance conveyance at significant energy and infrastructure cost.

Carbon footprint under conventional energy: When powered by fossil fuels, SWRO desalination has a significant carbon footprint that creates tension with climate objectives (Shelmer et al., 2023).

Land and permitting requirements: Large desalination plants require significant coastal land area and face complex environmental permitting requirements that can delay or prevent construction.

Lack of specific regulations of desalinated seawater supply for agricultural use in most countries.

Opportunities

Offshore desalination: Floating desalination plants and offshore systems can reduce competition for coastal land and simplify brine management in open-water environments.

Hybrid systems: Integration of SWRO with wastewater reuse (brine dilution with reclaimed water, combined brine-wastewater effluent discharge) and with renewable energy creates synergies that reduce both costs and environmental impacts (Crutchik & Campos, 2021).

Brine valorisation: Emerging technologies for recovery of minerals (lithium, magnesium, potassium, uranium) from desalination brine could provide valuable co-products that improve project economics (Politano el at., 2024).

Fit-for-purpose desalination for agriculture: Designing desalination systems specifically for agricultural quality standards (rather than potable standards) reduces agronomic risks and could reduce energy and post-treatment costs if other blending water sources are available, making desalination more economically competitive for irrigation.

Climate change-driven demand increase: As freshwater scarcity worsens in coastal regions due to climate change, desalination's competitive advantage over increasingly unreliable conventional sources will grow.

Threats

Energy price and availability risks: Large-scale desalination creates a structural dependency on affordable and reliable energy; energy price shocks or grid instability can dramatically increase production costs.

Chemical composition of DSW, particularly boron content, which can cause phytotoxicity in sensitive crops if not properly controlled. Additionally, low mineral content and sodium dominance may also lead to soil degradation, nutrient imbalances, or corrosion of infrastructure. These effects can be

mitigated through blending or post-treatment, but require careful management (Martínez Álvarez et al., 2023).

Marine ecosystem impacts: Cumulative brine discharge from multiple plants concentrated in semi-enclosed seas (Persian Gulf, Mediterranean) poses long-term risks to marine biodiversity that may trigger regulatory restrictions.

Climate change effects on seawater temperature and quality: Increasing sea surface temperatures accelerate biofouling of membranes and may alter seawater composition in ways that affect treatment efficiency.

Public opposition and social licence: Local communities near planned desalination sites often oppose development due to concerns about coastal impacts, noise, and visual intrusion.

Dependency and lock-in: Societies that become heavily dependent on desalination for water security are exposed to technology lock-in, price risk, and infrastructure vulnerability risks.

Table 3. SWOT for Non-Conventional Water Resources in Agriculture

	STRENGTHS	WEAKNESSES
REUSE	Nutrient supply; proximity; year-round availability; circular economy; proven technology; climate resilience	Quality variability; CECs; salinity risk; infrastructure cost; social acceptance; volume cap; inland uses
DESALINATION	Unlimited source; consistent quality; scalability; falling costs; renewable integration; strategic security	Energy intensity; brine management; agricultural quality adaptation; coastal dependency; cost
	OPPORTUNITIES	THREATS
REUSE	EU/Green Deal policy support; digital technology; nutrient recovery; growing water scarcity	CEC regulation uncertainty; market rejection; competition from conventional sources
DESALINATION	Offshore systems; hybrid approaches; brine valorisation; climate-driven demand	Energy price risks; marine ecosystem impacts; public opposition; dependency lock-in

5. Conclusions

Non-conventional water resources (NCWRs), reclaimed wastewater and desalinated water, represent essential instruments in the transition towards sustainable, climate-resilient water management for food production. Neither source can serve as a wholesale replacement for conventional freshwater, but in strategically defined contexts, particularly in water-scarce coastal and Mediterranean regions, they offer the prospect of substantially closing the growing gap between agricultural water demand and available supply, including NCWRs in the water mix available to agriculture.

On a purely volumetric basis, the potential is enormous but remains largely unrealised. If the approximately 188 billion m^3/year of treated wastewater currently generated globally could be fully reused (rather than only the 40.7 billion m^3 currently reused), this alone would significantly augment available water supplies, particularly at the basin and regional levels. Similarly, scaling up desalination to meet agricultural demands (where approximately 2,700 km^3/year is withdrawn for irrigation globally according to FAO) would require technological and economic advances of considerable magnitude. NCWRs cannot replace conventional freshwater systems at global scale with current technology and cost structures, but they can play a decisive role in specific geographic and sectoral contexts, particularly in water-scarce coastal regions, Mediterranean-type climates, and arid or semi-arid agricultural zones. The key challenge, therefore, is not purely volumetric but also one of governance, economics, technology deployment, regulatory alignment, and social acceptance.

Water reuse has the greater immediate potential for expansion at the global scale, given the existing infrastructure for wastewater collection and treatment in most developed countries, the proximity of WWTPs to irrigated agricultural areas, and the multiple co-benefits of nutrient supply and the circular economy. The key barriers are economic (infrastructure investment), regulatory (governance alignment, CEC frameworks), and social (public and market acceptance). Integrated, interdisciplinary, and territorial approaches are indispensable for resolving these barriers.

Desalinated seawater (DSW) emerges as a strategic and reliable resource that can decouple agricultural production from hydrological variability and provide a drought-resilient supply. Its application is especially suited to high-value, technologically advanced agricultural systems, where water costs represent a relatively small share of total production and where alternative resources are limited or unavailable.

From a technical and agronomic standpoint, desalination has reached a high level of maturity, with reverse osmosis enabling large-scale production of irrigation-quality water. However, its integration into agriculture requires careful management due to its specific physicochemical characteristics, including low

nutrient content and the presence of phytotoxic elements such as boron. These constraints necessitate post-treatment processes, blending strategies, and adapted fertigation practices to ensure soil health and crop productivity. While such measures can effectively mitigate potential risks, they also increase system complexity and operational requirements.

Economic and environmental considerations remain central to the long-term viability of DSW in agriculture. High energy consumption continues to drive production costs and associated GHG emissions, limiting the widespread adoption of this technology beyond high-return crops and regions with supportive policy frameworks. At the same time, the sustainability of desalination depends on factors such as proximity to irrigated areas, energy sources, and the management of environmental impacts, particularly brine disposal.

Overall, desalinated seawater represents a promising but context-dependent solution for agricultural water supply. Its successful implementation requires integrated strategies that combine technological innovation, economic feasibility, agronomic adaptation, and environmental safeguards. In this sense, DSW should not be viewed as a universal substitute for conventional resources, but rather as a complementary component within diversified and resilient water management systems to ensure long-term agricultural sustainability.

6. References

Abdelraouf, R.E., Abdou, M.A.A., Bakr, A., Hamza, A.E., Rashad, Y.M., Abd-ElGawad, A.M., Hafez, M.; Ragab, R. 2024. Enhancing Tomato Production by Using Non-Conventional Water Resources within Integrated Sprinkler Irrigation Systems in Arid Regions. Atmosphere, 15, 722.

Ait-Mouheb, N., Mayaux, P.-L., Mateo-Sagasta, J., Hartani, T., & Molle, B. 2020. Water reuse: A resource for Mediterranean agriculture. In Water Resources in the Mediterranean Region (pp. 107–136). Elsevier. https://doi.org/10.1016/B978-0-12-818086-0.00005-4

Alcaide, C., Fernández García, I., González Perea, R., Camacho Poyato, E., Rodríguez Díaz, J.A. 2019. REUTIVAR: Model for Precision Fertigation Scheduling for Olive Orchards Using Reclaimed Water. Water. 11, 2632

Alcaide, C., Fernández García, I., Martín, I. Camacho Poyato, E., Rodríguez Díaz, J.A. 2022. Spatio-temporal analysis of nitrogen variations in an irrigation distribution network using reclaimed water for irrigating olive trees. Agricultural Water Management, 262, 107353

Antiñolo Bermúdez, L., Leyva Díaz, J.C., Martín Pascual, J., Muñío Martínez, M.d.M., Poyatos. 2022 Study of the Potential for Agricultural Reuse of Urban Wastewater with Membrane Bioreactor Technology in the Circular Economy Framework. Agronomy, 12, 1877.

Aznar-Sánchez, J.A, Belmonte-Ureña, L.J, Velasco-Muñoz J.F., Valera, D.L. 2021. Farmers' profiles and behaviours toward desalinated seawater for irrigation: Insights from South-east Spain. Journal of Cleaner Production 296, 126568.

Barlow, S. M., Boobis, A. R., Bridges, J., Cockburn, A., Dekant, W., Hepburn, P., Houben, G. F., König, J., Nauta, M. J., Schuermans, J., & Bánáti, D. 2015. The role of hazard- and risk-based approaches in ensuring food safety. Trends in Food Science & Technology, 46(2), 176–188. https://doi.org/10.1016/j.tifs.2015.10.007

Ben-Gal, A., Yermiyahu, U., Cohen, S. 2009. Fertilization and blending alternatives for irrigation with desalinated water. J Environ Qual 2009, 38, 529–36.

Berbel, J., Mesa Pérez, E., Simón, P. 2023. Challenges for Circular Economy under the EU 2020/741 Wastewater Reuse Regulation. Global Challenges, 7, 7: 1-12

Boutagayout, A., Hamdani, A., Boutgayout, I., Adiba, A. 2025. Towards sustainable water management in Morocco: assessing resources, challenges, and adaptation strategies. Frontiers in Sustainable Food Systems, 10, 3389.

Cadena Aponte, F., Plaza Bolaños, P., Agüera, A., Nahim Granados, S., Berruti, I., Abeledo-Lameiro, M.J., Polo López, M.I. 2025. From the Reclaimed Water Treatment Plant to Irrigation in Intensive Agriculture Farms: Assessment of the Fate of Antibiotics, Antibiotic Resistance Bacteria and Genes, and Microbial Pathogens at Real Scale. Environ. Sci. Technol., 59, 19953−19965

California State Water Resources Control Board. 2000. California Water Recycling Criteria (Title 22, Division 4, Chapter 3).

Capilla, J.M. 2022 Study of the Potential for Agricultural Reuse of Urban Wastewater with Membrane Bioreactor Technology in the Circular Economy Framework. Agronomy, 12, 1877.

Carter, L., Dennis, S., Allen, K. et al. 2024. Mitigating Contaminant-Driven Risks for the Safe Expansion of the Agricultural Sanitation Circular Economy in an Urbanizing World. ACS EST Water, 4, 1166−1176

Crutchik, D., Campos, J.L. 2021. Municipal Wastewater Reuse: Is it a Competitive Alternative to Seawater Desalination? Sustainability, 13, 6815.

Daghari, H., Janson, A., & Bouzidi, Y. 2022. Assessment of desalination as an alternative water supply for agriculture in arid regions. Water, 14(6), 1712.

De las Heras, J., Mañas, P. 2020. Reclaimed Wastewater to Irrigate Olive Groves and Vineyards: Effects on Soil Properties. Agronomy 2020, 10, 649

Declercq, R., Loubier, S., Condom, N., Molle, B. 2020. Socio-Economic Interest of Treated Wastewater Reuse in Agricultural Irrigation and Indirect Potable Water Reuse: Clermont-Ferrand and Cannes Case Studies' Cost–Benefit Analysis. Irrig. and Drain., 69 (Suppl. 1): 194–208

Elimelech, M., Phillip, W.A. 2011.The future of seawater desalination: energy, technology, and the environment. Science, 333, 712–7.

European Food Safety Authority. 2016. Hazard vs. Risk. https://www.efsa.europa.eu/en/discover/infographics/hazard-vs-risk.

European Parliament, & Council of the European Union. 2020. Regulation (EU) 2020/741 of the European Parliament and of the Council on minimum requirements for water reuse. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32020R0741

Expósito, A., Lorenzo Lopez, A. M., & Berbel, J. 2024. How much does reclaimed wastewater cost? A comprehensive analysis for irrigation uses in the European Mediterranean context. Water Reuse, 14(3), 434–447. https://doi.org/10.2166/wrd.2024.040

FAO (Food and Agriculture Organization of the United Nations). 2017. Water for Sustainable Food and Agriculture. ISBN 978-92-5-109977-3

Fernandes, E., Cunha Marques, R. 2023. Review of Water Reuse from a Circular Economy Perspective. Water. 15, 848.

Gallego-Elvira, B., Reca, J., Martin-Gorriz, B., Maestre-Valero, J.F. and Martinez-Alvarez, V. 2021. Irriblend-DSW: A decision support tool for the optimal blending of desalinated and conventional irrigation waters in dry regions. Agricultural Water Management, 255, 107012.

Ghaffour, N., Bundschuh, J., Mahmoudi, H., Goosen, M.F.A. 2015. Renewable energy-driven desalination technologies: a comprehensive review on challenges and potential applications of integrated systems. Desalination, 356, 94–114.

Gómez Lucena, I., Camacho Poyato, E., Martín, I. Draissi, K.F., Rodríguez Díaz, J.A. 2024. NITRINET: A predictive model for nitrification in reclaimed water distribution in pressurised irrigation networks. Agricultural Water Management, 302,108982

GWI. 2023. Desalination Markets. Global Water Intelligence (GWI)

Hafez, M.; Ragab, R. 2024. Enhancing Tomato Production by Using Non-Conventional Water Resources within Integrated Sprinkler Irrigation Systems in Arid Regions. Atmosphere, 15, 722.

Ho, J., Ahmadi, J., Hübner, U., Tiehm, A., Drewes, J. 2024. Assuring reclaimed water quality using a multi-barrier treatment train according to the new EU non-potable water reuse regulation. Water Research, 267, 122429

Huerta M, Teijeiro MT, Kurek M, Campos M, Brito da Luz P, Cancela JJ (2025). Analysis of Strategies/Policies for the Use of Reclaimed Water-SUDOE. I-ReWater project (S1/2.5/E0136). 50 p.. URL: https://hdl.handle.net/10347/40809

INE, 2023.Spanish National Institute of Statistics [WWW Document]. URL https://www.ine.es/jaxi/Datos.htm?tpx=53450

International Organization for Standardization. 2018. ISO 20426: Guidelines for health risk assessment and management for non-potable water reuse.

International Organization for Standardization. 2020. ISO 16075: Guidelines for treated wastewater use for irrigation projects.

Jones, E., Qadir, M., van Vliet, M. T. H., Smakhtin, V., Kang, S. M. 2019. The state of desalination and brine production: A global outlook. Science of The Total Environment, 657, 1343-1356.

Jones, E.R., van Vliet, M.T.H., Qadir, M., Bierkens, M.F.P. 2021. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. Earth Syst. Sci. Data, 13, 237–254

Kurihara, M. 2021. Current Status and Future Trend of Dominant Commercial Reverse Osmosis Membranes. Membranes, 11, 906

Lahav, O., Birnhack, L. 2007. Quality criteria for desalinated water following post treatment. Desalination 207, 286–303.

Lapuente, E. 2012. Full cost in desalination. A case study of the Segura River Basin. Desalination, 300, 40–5.

López-Serrano, M.J., Velasco-Muñoz, J.F., Aznar-Sánchez, J.A., Román-Sánchez, I.M. 2021. Economic Analysis of the Use of Reclaimed Water in Agriculture in Southeastern Spain, A Mediterranean Region. Agronomy, 11, 2218.

Macedo, H.E., Lehner, L., Nicell, J., et al. 2022. Distribution and characteristics of wastewater treatment plants within the global river network. Earth Syst. Sci. Data, 14, 559–577

Maffettone, R., & Gawlik, B. M. 2022. Technical Guidance Water Reuse Risk Management for Agricultural Irrigation Schemes in Europe. https://dx.doi.org/10.2760/590804

Maki, A., Pedrero, F., Hafsi, M., Guerber, F. 2025. Desalination for agriculture development: Addressing opportunities and challenges in the context of changing climate and the global agricultural commodity market – Expert consultation workshop report. Tunis, FAO. https://doi.org/10.4060/cd4781en

Marcantonio, C., Mangiagli, G., Boni, M.R., et al. 2025. Are we ready for the application of the EU Regulation on wastewater reuse in agriculture? A techno-economic preliminary evaluation based on a case-study. Journal of Environmental Management. 373, 123973

Martin-Gorriz, B., Soto-García, M., Martínez-Alvarez, V. 2014. Energy and greenhouse-gas emissions in irrigated agriculture of SE (southeast) Spain. Effects of alternative water supply scenarios. Energy, 77, 478–88.

Martínez-Alvarez V., Maestre-Valero J.F., González-Ortega M.J., Gallego-Elvira, V., Martin-Gorriz B. 2019. Characterization of the Agricultural Supply of Desalinated Seawater in Southeastern Spain. Water, 11, 1233.

Martínez-Alvarez, V., González-Ortega, M.J., Martin-Gorriz, B., Soto-García, M., Maestre-Valero, J.F. 2018. Seawater desalination for crop irrigation—Current status and perspectives. Editor(s): Veera Gnaneswar Gude. In: Emerging

Technologies for Sustainable Desalination Handbook, Butterworth-Heinemann, 2018, 461-492.

Martínez-Alvarez, V., Imbernón-Mulero, A., Gallego-Elvira, B., Soto-García, M., Maestre Valero, J.F. 2023. Multidisciplinary assessment of the agricultural supply of desalinated seawater in south-eastern Spain. Desalination, 548, 116252.

Martínez-Álvarez, V., Imbernón-Mulero, A., Maestre-Valero, J.F.; Ben Abdallah, S., Gallego-Elvira, B. 2023. Agronomic Analysis of the Replacement of Conventional Agricultural Water Supply by Desalinated Seawater as an Adaptive Strategy to Water Scarcity in South-Eastern Spain. Agronomy,13, 2878.

Martínez-Alvarez, V., M., Maestre-Valero, J.F. 2025. Irrigation with non-conventional water. In Engineering, Water and Food Nexus. Eds. Silva, A., Gonçalves, J.M. World Federation of Engineering Organizations (WFEO), 2025, 117-133.

Martínez-Alvarez, V.; González-Ortega, M.J.; Martin-Gorriz, B.; Soto-García, M.; Maestre-Valero, J. F. 2017. The use of desalinated seawater for crop irrigation in the Segura River basin (South-eastern Spain). Desalination, 422, 153–164.

Michetti, M., Raggi, M., Guerra, E., Viaggi, D. 2019. Interpreting Farmers' Perceptions of Risks and Benefits Concerning Wastewater Reuse for Irrigation: A Case Study in Emilia-Romagna (Italy). Water, 11, 108

MITECO, 2021. National Plan for Water Treatment, Sanitation, Efficiency, Water Conservation and Reuse.

Politano, A., Al-Juboori, R.A., Alnajdi, S. et al. 2024. 2024 roadmap on membrane desalination technology at the water-energy nexus. Journal of Physics Energy, 6, 2

Poustie, A., Yang, Y., Velburg, P., Pagilla, K., Hanigan, D. 2020. Reclaimed wastewater as a viable water source for agricultural irrigation: A review of food crop growth inhibition and promotion in the context of environmental change. Science of the Total Environment. 739, 139756

Radini, S., Marinelli, E., Akyol, Ç. et al., 2021. Urban water-energy-food-climate nexus in integrated wastewater and reuse systems: Cyber-physical framework and innovations. Applied Energy, 298, 117268

Ragab, R. 2023. The global challenges facing the water resources and irrigation sector. 4th African Regional Conference on Geosynthetics (GeoAfrica 2023). E3S Web Conf. 368

Rodríguez-Villanueva, P., Sauri, D. 2021. Wastewater Treatment Plants in Mediterranean Spain: An Exploration of Relations between Water Treatments, Water Reuse, and Governance. Water, 13, 1710

Rodríguez, P., Palma, D., Poch, M., Cugueró-Escofet, M. Á., & Sauri, D. 2019. The geographical context of wastewater treatment and reuse: a benchmarking analysis for Spanish Mediterranean Wastewater Treatment Plants. Boletín de la Asociación de Geógrafos Españoles, 82, 2795, 1–30.

Savchenko, O. M., Kecinski, M., Li, T., & Messer, K. D. 2019. Reclaimed water and food production: Cautionary tales from consumer research. Environmental Research, 170, 320–331. https://doi.org/10.1016/J.ENVRES.2018.12.051

Shaffer, D.L., Yip, N.Y., Gilron, J., Elimelech, M. 2012. Seawater desalination for agriculture by integrated forward and reverse osmosis: improved product water quality for potentially less energy. J Membr Sci 415–416, 1–8.

Shahabi, M.P., McHugh, A., Anda, M., Ho, G. Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy. Renew Energy 67, 53–8.

Shemer, H.; Wald, S.; Semiat, R. 2023. Challenges and Solutions for Global Water Scarcity. Membranes, 13, 612

Soto-García, M., Martin-Gorriz, B., García-Bastida, P.A., Alcón F., Martínez-Alvarez, V. 2013. Energy consumption for crop irrigation in a semiarid climate (south-eastern Spain). Energy, 55, 1084–93.

Spiritos E, Lipchin C. 2013. Desalination in Israel. In: Water policy in Israel: context, issues and options. Dordrecht, Netherlands: Springer Publishing, 2013, 101–123.

Suwaileh, W., Johnson, D., Hilal, N. 2020. Membrane desalination and water re-use for agriculture: state of the art and future outlook. Desalination, 491, 114559.

United Nations. 2023. Water Scarcity, the Climate Crisis and Global Food Security: A Call for Collaborative Action. https://www.un.org/en/un-chronicle/water-scarcity-climate-crisis-and-global-food-security-call-collaborative-action

Ventura, D., Consoli., S., Barbagallo, S., et al. 2019. How to Overcome Barriers for Wastewater Agricultural Reuse in Sicily (Italy)? Water, 11, 335.

Villar-García, A. del, 2016. Reutilización de aguas regeneradas: aproximación a los costes de producción y valoración de su uso.(In English: *Reuse of reclaimed water: an analysis of production costs and an assessment of its use*). Agua y Territ. 70–79. https://doi.org/10.17561/at.v0i8.3297

Wang, C., Wang, L., Dong, L., Shon, H.K., Kim, J. 2025. Specific energy consumption of seawater reverse osmosis desalination plants using machine learning. Desalination 602, 118654.

Yermiyahu, U., Tal, A., Ben-Gal, A., Bar-Tal, A., Tarchitzky, J., Lahav, O. 2007, Rethinking desalinated water quality and agriculture. Science, 318, 920–921.

Yuan, J., Van Dyke, M.I., Huck, P.M. 2017. Identification of critical contaminants in wastewater effluent for managed aquifer recharge. Chemosphere. 172: 294-301

Zolghadr-Asli, B., McIntyre, N., Djordjevic, S., Farmani, R., Pagliero, L., Martínez-Alvarez, V., Maestre-Valero, JF. 2023. A review of limitations and potentials of desalination as a sustainable source of water. Environ Sci Pollut Res Int 30 (56),118161-118174.