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Future scenarios for sustainable water management in Mediterranean agricultural systems: a life cycle case study on water reuse in Northern Italy

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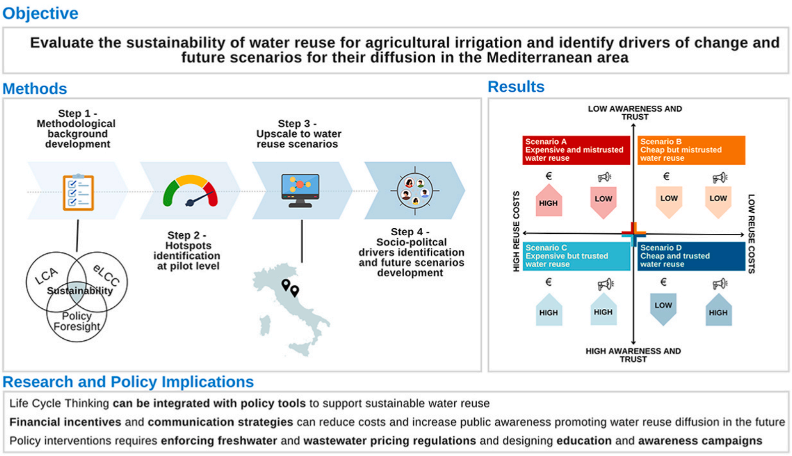
HIGHLIGHTS

- The study applies life cycle thinking and policy foresight to water reuse.
- Water reuse reduces impacts of water-intensive crops like tomatoes.
- All scenarios exceed planetary boundaries in several impacts.
- Including externalities makes water reuse cheaper.
- Financial incentives and communication are key enablers for water reuse use.

GRAPHICAL ABSTRACT



Objective

Evaluate the sustainability of water reuse for agricultural irrigation and identify drivers of change and future scenarios for their diffusion in the Mediterranean area

Research and Policy Implications

Life Cycle Thinking **can be integrated with policy tools** to support sustainable water reuse

Financial incentives and **communication strategies** can reduce costs and increase public awareness promoting water reuse diffusion in the future

Policy interventions requires **enforcing freshwater** and **wastewater pricing regulations** and designing **education** and **awareness campaigns**

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ABSTRACT

Water reuse is a promising strategy to mitigate water scarcity in Mediterranean agriculture yet its uptake remains limited due to low public acceptance, high treatment costs and strict safety regulations. While innovative technologies are emerging, systematic long-term evaluation of their environmental and economic implications are still scarce. This study assesses the sustainability of water reuse scenarios for irrigation in tomato production through a case study in Italy, using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) to compare reuse-based and conventional irrigation systems. Quantitative analysis was combined with a qualitative foresight involving experts from seven Mediterranean countries to translate the findings into future scenarios and actionable strategies. Results indicate that water reuse scenarios consume 0.03 m^3 of water per kg of tomatoes, compared with nearly 1 m^3 per kg in conventional systems. From a planetary boundaries perspective, both approaches still exceed safe environmental thresholds in several impact categories. Economically, water reuse slightly raises tomato production costs (0.15 €/kg vs 0.14 €/kg), but current scenario entails higher human health

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and ecosystem costs (0.06 €/kg vs 0.04 €/kg). The foresight exercise co-designed four qualitative future scenarios for water reuse, emphasising the importance of financial incentives and targeted communication to foster broader adoption. Overall, integrated sustainability assessment combined with experts-based analysis can support evidence-based decision-making and support policy measure to advance sustainable water reuse in Mediterranean agriculture.

1. Introduction

Agricultural water management plays a relevant role in the transformation of food systems and the advancement of sustainable development goals (Ringler et al., 2022). Water imbalances, exacerbated by extreme events under a climate change scenario, are expected to have profound effects on global populations, with significant economic repercussions (Trancoso et al., 2024). Water reuse (or reclamation), the process of treating wastewater (WW) for beneficial purposes (*e.g.* agricultural irrigation), has emerged as a potentially valuable strategy for enhancing water quality, mitigating water scarcity, and offering a promising alternative water supply (Christou et al., 2024). In water-scarce regions such as the Mediterranean, water reuse strategies have been particularly implemented in countries like Jordan (Alfarra et al., 2011) and Cyprus (Christou et al., 2014). However, their adoption is less widespread in other Mediterranean countries, with some examples in Spain and Italy (Fito and Van Hulle, 2021; Maffettone and Gawlik, 2022).

From June 2023, the implementation of the new EU regulation on minimum requirements for water reuse has aimed to promote efficient water resource utilisation. It also offers guidance to market operators and practitioners, complementing existing EU Water Policy directives, including the Water Framework Directive (2000/60/EC) and the Urban Wastewater Treatment Directive (91/271/EEC). Despite the considerable and acknowledged potential benefits of water reuse, its adoption remains significantly below optimal levels (Gawlik, 2017). Technical, infrastructural, and financial barriers (Cipolletta et al., 2021; Voulvoulis, 2018) continue to limit the widespread implementation of innovative water reuse technologies, owing to the high costs of implementation and the challenges in meeting stringent requirements for safe reuse, particularly in countries such as Italy (Licciardello et al., 2018). Although novel technologies continue to emerge to ensure environmental and human safety (Cantarella, 2019; Molinos-Senante et al., 2011), interest is growing in assessing the broader systemic impacts of implementing water reuse projects (Corominas, 2020; Corominas et al., 2013).

Life Cycle Assessment (LCA) has proven to be an effective decision support tool for water reuse projects in agricultural systems (Crovella et al., 2024; Kalboussi et al., 2022) by quantifying environmental impacts over the entire life cycle of the services. Life cycle approaches also proved to be effective in supporting the analysis of circular systems and inform circular economy strategies (Mondello et al., 2024; Opher et al., 2019). Numerous studies have used LCA to demonstrate the potential benefits of reclaimed water for irrigation, including reduced eutrophication (Moretti et al., 2019), reductions in GHG emissions (Miller-Robbie et al., 2017; Rodriguez-Garcia et al., 2011), and savings from avoided fertiliser use (Muñoz et al., 2010). Other research has shown crop-specific advantages, such as improved outcomes in cereals (Romeiko, 2019) and cucumbers (Azeb et al., 2020), while also emphasising trade-offs and context-dependent impacts (Kalboussi et al., 2022) shaped by treatment technologies, energy mix, and site conditions (Maeseele and Roux, 2021).

Despite ongoing efforts to evaluate the environmental impacts of services, a comprehensive sustainability assessment necessitates the integration of social and economic dimensions (Kloepffer, 2008; Weidema, 2006) to fully understand the multifaceted implications of sustainability interventions across systems. Furthermore, participatory processes led by stakeholders are relevant in contextualising sustainability assessments at the local scale (Reed et al., 2006). These processes enable the bridging of knowledge between domain experts and end users, fostering more grounded and inclusive assessments.

In the Mediterranean region, some life cycle-based studies have extended the scope of sustainability evaluations beyond purely environmental aspects, focusing on non-potable water reuse projects (Table 1). Many of these incorporate Life Cycle Costing (LCC) methodologies to examine both internal (Foglia et al., 2021) and external (Canaj et al., 2021) financial costs of water reuse projects. Such approaches complement LCA by monetising externalities and providing a fuller picture of economic feasibility (Nguyen et al., 2016). For instance, Canaj et al. (2021), by illustrating a case study in Southern Italy confirmed that combining LCA with external cost valuation can identify trade-offs between treatment-related energy costs and avoided damages from reduced marine eutrophication and groundwater depletion. Hence, environmental and conventional costs integration allows for evaluating the viability of water reuse initiatives and identifying the cost burdens experienced by stakeholders involved in agricultural and domestic water supply systems (Gilboa et al., 2023; Jiménez-Benítez et al., 2024).

Attempts to incorporate social dimensions into sustainability assessments have been made in evaluating non-potable water reuse for domestic use. These efforts include stakeholders' participation to investigate social impacts. Opher et al. (2018, 2019) investigated the social benefits of various domestic non-potable water reuse options in Israel, engaging a panel of 20 experts. Muhammad Anwar et al. (2021) explored the environmental, economic and social implications of providing water reuse services in a refugee camp in Jordan, interviewing eight experts. However, studies embedding Life Cycle Thinking (LCT) sustainability assessments into stakeholders' participation for agricultural water reuse remain limited.

In parallel, an emerging body of literature highlights the value of combining LCA with future-oriented approaches for the early sustainability evaluation of novel products, technologies, and systems (Bisinella et al., 2021). Foresight, in particular, has gained prominence in strategic decision-making in response to global environmental challenges (Wiebe et al., 2018) as it enables the integration of future studies and sustainability assessments to address long-term development goals (Arushanyan et al., 2017; Höjer et al., 2008). While foresight studies on water reuse do exist (van Vliet and Kok, 2015) no study has integrated life cycle methods with qualitative foresight approaches for water management scenarios. Life cycle-based assessments provide quantitative evidence of environmental and economic performance, but they do not capture the contextual and institutional factors that shape long-term implementation. As a result, barriers and enabling conditions for the wider adoption of water reuse in the Mediterranean remain poorly understood, and the potential contribution of such solutions to long-term sustainability goals has yet to be systematically assessed. To addresses this gap in long-term assessments of water reuse in agriculture, this study evaluates the sustainability of innovative reuse scenarios in the Mediterranean, using experimental trials in Italy as a case study. It is guided by three research questions: *(1)* To what extent can water reuse for agricultural irrigation in Italy reduce environmental impacts compared to conventional freshwater use both in absolute and comparative terms? *(2)* How do the economic costs of water reuse compare with those of conventional irrigation when environmental externalities are considered? and *(3)* What drivers of change are most critical for enabling the wider adoption of water reuse in Mediterranean agriculture by 2050? To answer these questions, the study applies LCA and environmental LCC methodologies to assess innovative wastewater treatment technologies that integrate nature-based and intensive solutions. The analysis considers a simulated full-scale scenario treating 800 m^3/day of municipal wastewater for irrigation in the Emilia-Romagna region, compared against a baseline of conventional wastewater treatment and freshwater use for irrigation. Results are evaluated in absolute terms, considering the thresholds set by planetary boundaries (Rockström et al., 2009). Finally, building on the sustainability assessment results, the study integrates a stakeholder-led qualitative foresight to develop expert-based explorative scenarios, identifying the policy enablers and key drivers that could support the diffusion of water reuse in Mediterranean agriculture by 2050.

2. Methods

To evaluate the long-term sustainability of the innovative water reuse solutions, this study first conducted a quantitative assessment grounded in LCT. LCA and eLCC were applied to identify environmental and economic hotspots, as well as the main drivers influencing the performance and feasibility of water reuse projects. Building on these findings, an expert-based qualitative foresight exercise was undertaken. The drivers identified in the LCT-based assessment were used as inputs for the development of explorative future scenarios, co-constructed with stakeholders to capture contextual, institutional, and socio-political dimensions that cannot be addressed through quantitative methods alone. This sequential integration of LCA/eLCC with foresight enabled a more comprehensive appraisal of long-term sustainability, linking technical performance with policy relevance and system-level transitions.

2.1. Environmental and financial analyses

LCA is a standardised method that aims to quantify the environmental impacts of a product or a process over its entire life cycle (ISO, 2006b, 2006a). This study performs an LCA following an attributional approach to investigate possible environmental impacts of the life cycle of the novel water reuse technologies. An eLCC, following Hunkeler et al. (2008) and Swarr et al. (2011), was applied grounding on LCA phases by applying a set of monetisation factors to the footprint indicators identified to measure and value environmental costs and benefits to support decision-making (Galgani et al., 2021). Following ISO:14040 and ISO:14044, the four steps of LCA and LCC application are outlined below while more detailed methodological information is provided in *Supplementary Materials I and II.*

2.1.1. Goal and scope definition

The study, conducted within the project FIT4REUSE,[1] evaluates the economic and environmental impacts of alternative scenarios: (a) water reuse (WR) scenarios using innovative treatment technologies for agricultural irrigation, and (b) a business-as-usual scenario (BAU) with conventional treatment and groundwater irrigation. The purpose is to inform public authorities with evidence on sustainability performance. The methodological approach is twofold. First, technologies are assessed at pilot scale using 1 m^3 of treated wastewater as Functional Unit (FU). Three pilot systems designed to meet EU Class A standards of EU *Regulation 2020/741*, assuming a 20-year lifespan (Molinos-Senante et al., 2010) are included. Second, the technologies are upscaled and assessed in a full-scale irrigation scenario. This upscaling is conducted through a system expansion approach using 1 kg of tomatoes irrigated with reclaimed water as the functional unit. Tomatoes were selected owing to their high-water demand and regional significance in Emilia-Romagna. Mass-based functional units in the context of water reuse have been adopted in previous studies (*e.g.*, Moretti et al., 2019; Kalboussi et al., 2022) to evaluate irrigation scenarios and to account for the function or service provided by the recycled product. The system boundaries (Fig. 1) comprise construction, operation, and end-of-life phases at pilot scale and extend from municipal wastewater production to field-level irrigation at full scale.

2.1.2. Experimental trials

The analysis considered two intensive technologies - *Upflow Anaerobic Sludge Blanket Reactor (UASB)* and *Molecularly Imprinted Polymers (MIP)* - and on a nature-based solution - *Aerated Constructed Wetland (ACW)* at pilot level. UASB and ACW were implemented in *Falconara Marittima* (Marche Region) by Università Politecnica delle Marche,

Table 1
Existing life cycle-based studies evaluating other sustainability aspects beyond environmental for non-potable water reuse projects in the Mediterranean.

Study	Aim	WW End-use	Country	Dimension				Stakeholders Participation	
				Environmental	Economic	Social	Policy	Y/N	Sample Size
Opher et al. (2018)	To identify social benefits and impacts of four alternative approaches to urban domestic non-potable water reuse	Domestic	Israel			X		Y	20
Opher et al. (2019)	To examine the sustainability of utilising reclaimed domestic wastewater in urban households	Domestic	Israel	X	X	X		Y	20
Foglia et al. (2021)	To investigate the environmental and economic impacts of possible scenarios to enable reclaimed water reuse for agriculture	Agriculture	Italy	X	X			N	–
Canaj et al. (2021)	To assess the environmental impacts and external costs of reuse of wastewater for irrigation	Agriculture	Italy	X	X			N	–
Muhammad Anwar et al. (2021)	To compare the environmental, economic, and social implications of different WASH services	Domestic	Jordan	X	X	X		Y	8
Gilboa et al. (2023)	To assess the environmental and economic aspects of water reuse	Domestic	Israel	X	X			N	–
Jimenez-Benítez et al. (2024)	To assess the technical, economic and environmental feasibility of UF membranes as tertiary treatment for urban wastewater recovery	Agriculture	Spain	X	X			N	–
This article	To evaluate the sustainability of innovative solutions to co-design future scenarios for water reuse diffusion	Agriculture	Italy[a]	X	X		X	Y	62

[a] Results of the policy foresight exercise refer to the whole Mediterranean area.

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[1] The project FIT4REUSE, funded by the European Commission Prima programme under Grant Agreement No. 1823, aimed to provide safe, sustainable and accepted ways of water supply for the Mediterranean basin by exploiting non-conventional water resource.

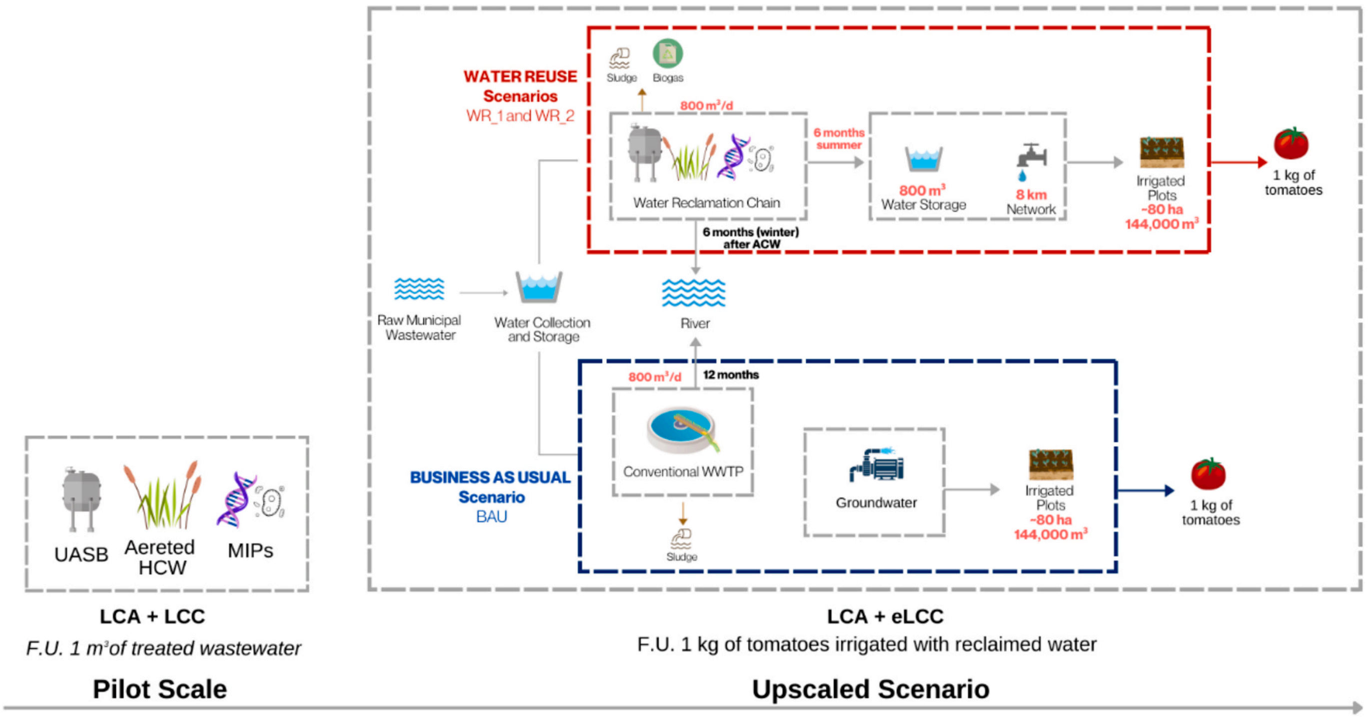

Fig. 1. System boundaries of the Water Reuse (WR) and Business-as-usual (BAU) scenarios assumed in the analysis. Detailed descriptions of the scenarios can be found in Table 2.

while MIPs were tested in *Granarolo dell'Emilia* (Emilia Romagna) by the University of Bologna. UASB acts as an anaerobic digester treating municipal wastewater and recovering biogas for energy (Foglia et al., 2021). MIPs are synthetic polymers used to remove micropollutants like diclofenac (Cantarella et al., 2019). ACWs replicate natural wetlands, using plants and substrates to clean wastewater, with aeration enhancing performance (Andreo-Martínez et al., 2017). Treatment capacities were 0.07 m^3/day (UASB), 0.6 m^3/day (ACW), and 0.01 m^3/day (MIPs). Pollutant removal efficiency is detailed in *Supplementary Material, Table A*, and evidenced in Mancuso et al. (2024) and Parlapiano et al. (2024).

2.1.3. Full-scale scenarios

Pilot-scale technologies were upscaled to simulate plausible water reuse scenarios for agriculture in Northern Italy. The analysis compared three alternative scenarios: one **BAU scenario**, where irrigation depends on groundwater resources and wastewater is treated using conventional technologies, and two **water reuse scenarios**, in which the novel technologies are implemented. The main characteristics of these scenarios are summarised in Fig. 1 and Table 2. Key assumptions include no water losses and sludge disposed of via landfill. Tomato production (modelled using Ecoinvent v3.11 process for tomato production in Italy) conditions are assumed to be identical across all scenarios, except for the source of irrigation water and the associated reduction in fertiliser requirements in the WR scenarios. Fertiliser savings and emission reductions (*Table B, Supplementary Materials I)* are estimated using results obtained from tomato crop trials with reclaimed water in Northern Italy (Odone et al., 2024). In the water balance treated water discharged to the environment is excluded, as it is returned with minimal net impact. Groundwater abstraction is included in the BAU scenario, reused water in WR scenarios is excluded since it originates outside the system boundaries and tap water is not characterised by LCA methods. In both WR scenarios, the water output flows were modelled following the guidelines provided by Nemecek et al. (2019).

2.1.4. Data collection

Primary data were collected over two years (from 2020 to 2022) through a dedicated data collection protocol distributed to the three researchers responsible for the experimental trials. These data were validated by the experts involved in the trails and complemented with secondary datasets from Ecoinvent v3.11. To reflect the Italian context as closely as possible, country-specific processes were selected whenever available, for example, the Italian electricity mix or fertiliser production. Where national data were not available, European datasets were used, and global datasets were adopted only as a last resort Detailed inventories of the three technologies are reported in *Supplementary Materials I, Table C, D, and E and Supplementary Materials II.*

2.1.5. Life cycle impact assessment

The Product Environmental Footprint (PEF) methodology and SimaPro software v10.2 were used to classify and characterise the environmental impacts of the technologies This LCA methodological framework, recommended by the European Commission for the evaluation and communication of life cycle environmental attributes of products (EC/2021/9332), uses 16 midpoint Characterisation Factors (CFs) (*Supplementary Materials I, Table F)*. Characterised impacts were normalised and weighted into single scores for pilot-scale assessment, while characterised environmental impacts for the full-scale scenarios were investigated for water reuse related impact categories (Corominas, 2020).

Characterised LCA results were compared against their allocated shares of the planetary boundaries, to further analyse the environmental impact in absolute terms (Sala et al., 2020). The share allocated to the reference product (1 kg of irrigated processing tomato, PB_{tom}) were expressed through a function relating the total planetary boundaries per capita (PB_{capita}) to a ratio expressing the utility attributed to the reference product, by relating its average price (P) to the country GDP (Y) (Bjørn, Chandrakumar, et al., 2020) expressed in Equation (1).

$$PB_{tom} = \left(\frac{P}{Y}\right) * PB_{capita} \qquad \text{Equation 1}$$

Table 2
Assumptions and characteristics of the scenarios analysed. *WWTP: Wastewater Treatment Plant; PE: Population Equivalent.*

Scenarios Characteristics		Scenarios Assumptions		
Water Supply Steps		*WR_1*	*WR_2*	*BAU*
Water Inflow	Source	Municipal WWT effluent		Municipal WWT effluent; Groundwater
	Extraction	No extraction		Energy for GW extraction
	Transportation & Storage	Same for all scenarios		
Water Treatment	Water flow	800 m^3/d		
	WWT Capacity	5000 PE		
	Infrastructure	WWTP with innovative technologies (UASB, ACW, MIPs, UV)	WWTP with innovative technologies (UASB, ACW, UV)	*Ecoinvent v3.11* Conventional WWTP
	Type of treatment	Primary, secondary, tertiary/disinfection		Primary, secondary
	By-products	Biogas		None
	Sludge disposal	Dewatering + landfill		
Distribution to agricultural plots	Hydraulic network losses	Same for all scenarios		
	Water Storage & supply network	800 m^3 + Energy consumption for supply		Energy for irrigation
	Irrigation type	Mix surface, sprinkler and drip irrigation		
	Irrigation surface	~80 ha (tomatoes)		
	Water needs	144,000 m^3 (6 months)		
	Fertilizers	Avoided fertilisers[a] −37 % N, −1.3 %P −70 % K		Ecoinvent v3.11 – processing tomatoes production (IT)
Water Outflow	Discharge	River		

[a] Based on experimental trial results of Odone et al. (2024).

Italian monthly prices of tomatoes for 2024 were obtained from the European Commission AGRIDATA portal's API (European Commission, 2025). GDP estimates from the World Bank national accounts data, and OECD National Accounts data files (World Bank, 2023) and planetary boundaries estimates from Sala et al. (2020). Data and elaboration are presented in *Supplementary Materials III.*

A conventional Life Cycle Costing (LCC) analysis was employed to assess the costs of wastewater treatment at both pilot- and full-scale scenarios, considering Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) over a 30-year period, applying an interest rate of 1.5 %. Details of the cost categories considered are provided in *Supplementary Materials II*. Costs were reported as €/m^3 of reclaimed water and €/kg of tomatoes. In the full-scale scenarios, the eLCC complemented the LCA by monetising environmental externalities, following the formula proposed by Galgani et al. (2021) and multiplying the characterised LCA impacts by the PEF-compatible valuation factors provided by European Commission et al. (2020). These factors were selected because they represent the only set of monetary valuation coefficients explicitly designed for use in combination with the EF method (Amadei et al., 2021), thereby ensuring methodological consistency with LCA. At present, no regionalised valuation coefficients exist; EU-wide factors were therefore applied to ensure methodological consistency and comparability with other studies in line with the PEF framework. The coefficients were updated to 2023 values by using the Italian inflation rate and Consumer Price Indexes (*Table G, Supplementary Materials I*), as indicated in Amadei et al. (2021).Farm-gate prices for tomato production were taken from ISMEA Mercati, (2024).

Multifunctionality in systems like UASB (biogas production) was addressed via economic allocation, with biomethane valued at 230 €/GJ based on GSE and conversion factors from Cappelli et al. (2021). The wastewater price was set at 0.03 €/m^3 (Ozgun et al., 2021).

2.1.6. *Sensitivity analysis*

A Monte Carlo sensitivity analysis with 1000 iterations (Huijbregts, 1998) was conducted to evaluate variability in environmental outcomes across scenarios. Uncertainty values were derived from Ecoinvent's pedigree matrix. Nutrient savings variability (N, P, K) was modelled using triangular distributions based on Odone et al. (2024), following the approach of Beylot et al. (2018). A parallel sensitivity analysis tested variability in the eLCC using low and high monetisation coefficients retrieved from *Annex B* of European Commission et al. (2020) to assess valuation uncertainty.

2.2. *Policy foresight*

Foresight is a systematic, participatory process designed to inform present decision-making by anticipating future challenges and opportunities, thereby facilitating joint actions that support policymaking (Cook et al., 2014; Störmer et al., 2020; Wiebe et al., 2018). To explore potential future scenarios for the diffusion of water reuse in the Mediterranean region, the process followed three steps (Cook et al., 2014; Hines, 2016): (1) identifying key drivers of change through Delphi surveys; (2) building future scenarios; and (3) conducting an expert focus group to refine strategies and policies for water reuse adoption. Surveys and group facilitation were led by two researchers, respectively female and male PhD students, with qualitative research expertise. All qualitative methods adhered to the COREQ guidelines (Tong et al., 2007) with details reported in *Table H* of *Supplementary Materials I.*

2.2.1. *Step 1) delphi e-surveys*

The Delphi method is a structured expert survey methodology in which individuals' opinions are gathered through a series of iterative questions to achieve consensus (Mahajan et al., 1976). This method is particularly well-suited to questions requiring expert judgement, where multiple potential answers exist (Hakami, A., Ghiran, A., and Bontoux, 2020).

An extensive list of experts was compiled by leveraging the networks of partners involved in the FIT4REUSE project. The survey specifically targeted the seven Mediterranean countries where FIT4REUSE project case studies and water reuse applications were implemented, ensuring direct relevance to regional contexts. To broaden coverage and reduce potential bias, snowball sampling identified representatives from academia and research centres, non-governmental organisations (NGOs), private companies, farmers and/or farmers' associations, and public authorities within the water reuse sector. Experts were defined as individuals possessing specialised knowledge of water reuse practices and technologies and were selected to ensure both stakeholder diversity and balanced geographical representation. In line with the quintuple helix model (Carayannis and Campbell, 2012), efforts were made to achieve a heterogeneous panel by including voices from science, industry, policy, civil society, and the environment. This approach attempted to ensure that the Delphi surveys and subsequent focus groups captured a wide range of perspectives across the Mediterranean region.

An anonymous survey (*Figure A, Supplementary Materials I*) was distributed via FIT4REUSE channels to 52 (mailing list) and 108 (project multistakeholder platforms) recipients. Both channels included representatives from all identified stakeholder categories and ensured coverage of regional differences. The Delphi surveys were conducted in two rounds using the Qualtrics platform and were pilot tested by authors. Participants were informed about the researchers' purpose of the study and the methods of data processing. Round 1 (September to October 2022) garnered 64 responses, while Round 2, conducted two weeks later, received 22 responses. After exclusions (non-consent, < 25 % completion), 46 % of total responses, 47 valid responses remained. Demographics of participants are reported in Table 3.

The exercise aimed to reach expert consensus on the five key drivers of water reuse diffusion in the Mediterranean, drawing on 8 internal and 18 external factors (*Table I, Supplementary Materials I*) identified in the sustainability assessment and by the analysis of Berti Suman et al. (2023). Using a two-round ranking process, experts evaluated environmental, social, political, technological, and financial drivers following existing approaches in the literature (Padilla-Rivera et al., 2021). In Round 1, drivers were scored 1–5 (with 5 = most influential). Round 2 validated and refined the top-ranked drivers. Data were analysed using Microsoft Excel and visualised using Tableau software.

2.2.2. Step 2) scenarios building

Scenario analysis adopted a systemic approach, incorporating key drivers of change identified in previous steps. Scenarios offer multidimensional visions of the future, enabling participants to evaluate opportunities and threats associated with these drivers (Störmer et al., 2020). The authors contextualised the drivers from Delphi within potential megatrends—long-term forces observable today, likely to influence future developments. Megatrends were selected from the EU Megatrends Hub,[2] which identifies 14 global forces shaping the EU's strategic sectors. This informed the creation of a scenario matrix and the development of four future scenarios, accompanied by actionable strategies to achieve the most desirable outcome. The process followed established foresight practices (Mylona et al., 2016).

Table 3
Delphi e-surveys and focus groups participants demographics.

		Delphi Round 1	Delphi Round 2	Focus Group
Stakeholder Type	Public Authorities	16 (44 %)	3 (27 %)	1 (7 %)
	Academia and Research Centres	12 (33 %)	3 (27 %)	12 (80 %)
	Private Sectors (*e.g.,* consultancy)	6 (17 %)	1 (9 %)	2 (13 %)
	Farmers and Farmer Association	1 (3 %)	2 (18 %)	0
	NGOs	1 (3 %)	2 (18 %)	0
Country	France	4 (11 %)	1 (9 %)	1 (7 %)
	Greece	7 (19 %)	0 (0 %)	3 (20 %)
	Israel	7 (19 %)	1 (9 %)	0 (0 %)
	Italy	9 (25 %)	5 (45 %)	5 (33 %)
	Spain	5 (14 %)	1 (9 %)	1 (7 %)
	Tunisia	0 (0 %)	0 (0 %)	3 (20 %)
	Turkey	4 (11 %)	2 (18 %)	2 (13 %)
	Prefer/Did not respond	0 (0 %)	1 (9 %)	0 (0 %)
	Total	*36*	*11*	*15*

2.2.3. Step 3) focus group

Focus groups facilitate the exploration of social interactions and consensus-building through group discussions on predetermined topics (Kitzinger, 1995). A focus group of 15 water experts was convened to review the Delphi exercise results and the developed scenarios during the final FIT4REUSE meeting (convenience sampling). This group of experts was covering the majority of stakeholders category. The session was conducted in person and participants were divided into 5 subgroups and used a digital Miro board (*Supplementary Material I, Figure B*) to explore the developed scenarios.

A structured dashboard (*Supplementary Materials I, Figure C*) guided subgroup discussions on future scenarios, their likelihood, and preference rankings. Participants then co-developed policy strategies, drawing on literature (Hopson and Fowler, 2022; Mylona et al., 2016) and Regulation (EU) 2020/741 on water reuse, and identified key stakeholders. Insights were shared in a plenary session, with data recorded in Microsoft Excel. Table 3 shows the demographics of these assessments.

3. Results

3.1. Hotspots and recommendations from pilot scale analysis

The pilot-scale analysis identified environmental and financial hotspots in innovative wastewater treatment technologies. Energy consumption was the dominant contributor to environmental impacts across all systems (*Figure D, Supplementary Materials I*). MIPs were the most environmentally intensive due to the high energy demands of polymer synthesis, which accounted for 90 % of their impact. Chemical reagent disposal contributed an additional 10 %, mainly affecting global warming and resource depletion. Similar concerns were noted in ACW and UASB systems, where air compressors (81 %) and granular filters (53 %) significantly increased environmental burdens. ACW also produced notable greenhouse gas emissions (19 %) from nitrous oxide and methane. The LCC assessment (*Table J, Supplementary Materials I*) revealed major challenges for MIPs, with high chemical and energy requirements driving to elevated treatment costs (474.27 €/m^3). The most expensive stages were synthesis and hazardous waste disposal. In contrast, ACW were more affordable at 40.47 €/m^3, though energy remained a major cost. UASB systems were the most cost-effective at 17.13 €/m^3.

3.2. Scenarios analysis at full scale

3.2.1. Environmental impacts of water reuse scenarios

When scaling up the analysis, the results indicate that reusing water can reduce the environmental impacts of processing tomatoes production at farm gate. Fig. 2 presents the results of the LCA (also shown in S14 of *Supplementary material II*) and the environmental impacts of 1 kg of processing tomatoes under two water reuse scenarios (with and without MIPs) compared to a BAU scenario, in which fields are irrigated with groundwater and wastewater is discharged into the environment. The results demonstrate that the water reuse scenario can substantially reduce impacts on water resources. Specifically, while the BAU scenario depletes water resources by ~1 m^3 for every kilogram of tomatoes produced, WR scenarios result in a depletion of ~0.03 m^3.

WR scenarios show notable improvements across most impact categories. Acidification is reduced by 31 % in both scenarios, while the WR scenario without MIPs (WR_2) shows marginally greater reductions in climate change (−26 % vs. −24 %) and human toxicity (carcinogenic) (−26 % vs. −24 %) compared to WR_1. Reductions in ecotoxicity freshwater and freshwater eutrophication are minimal in both cases,

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[2] https://knowledge4policy.ec.europa.eu/foresight/tool/megatrends-hub_en .

Fig. 2. Environmental impacts of producing 1 kg of processing tomatoes under different scenarios of water management. Green lines and green areas show the thresholds of planetary boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article)

though WR_1 performs marginally better, reducing both by 3 % compared to 2 % under WR_2. Both scenarios present greater reduction in marine eutrophication (−16 %) compared to BAU.

When evaluating the impact on non-carcinogenic human toxicity, the analysis shows the potential effectiveness of MIPs in mitigating environmental impacts at a broader scale. The WR_2 exhibits a performance comparable to that of the business-as-usual scenario, with only a minor reduction of approximately 1 %. In contrast, the WR_1 scenario demonstrates a 15 % decrease in impact, primarily attributable to reduced concentrations of diclofenac in the water.

Although the WR scenarios resulted in reduced environmental impacts compared to the baseline, only three of the assessed impact categories (acidification, carcinogenic human toxicity, and water use) fell below the thresholds (green lines in Fig. 2) defined by planetary boundaries. Impacts in all other categories exceeded these limits, with freshwater ecotoxicity surpassing planetary boundaries by approximately 5000 %. Water use impacts in the BAU scenario were only 21 % below the planetary boundary, underscoring the potential of water reuse strategies to further reduce these impacts and increase the margin of safety relative to planetary limits.

3.2.2. *Environmental and financial costs of water reuse scenarios*

Water reuse remains more expensive than conventional irrigation, particularly when additional treatments to remove emerging pollutants are required. The financial analysis indicates that the cost of water under the BAU scenario is 0.51 €/m^3 compared to 2.40 €/m^3 (WR_1) and 0.79 €/m^3 (WR_2) of reclaimed water (see *Supplementary Materials II*). Table 4 presents the results of the financial analysis of upscaled water reuse scenarios. While the cost of producing 1 kg of processing tomatoes at the farm gate using conventional irrigation (BAU scenario) is 0.14 €/kg (ISMEA Mercati, 2024), the use of treated wastewater increases production costs to 0.18 €/kg and 0.15 €/kg.

When environmental impacts are monetised, the cost of producing processing tomatoes is slightly lower under WR_1 scenario compared to the BAU (0.19 €/kg vs 0.20 €/kg). The scenario incorporating MIPs (WR_2) remains comparatively more expensive, with a total cost of 0.22 €/kg. Furthermore, sensitivity analysis reveals that the application of high monetisation factors can increase the cost of irrigation using conventional water to 0.56 €/kg. By contrast, the two WR scenarios exhibit lower variability, with maximum estimated costs of 0.29 €/kg and 0.27 €/kg, respectively, suggesting that environmental valuation assumptions may influence value of conventional irrigation practices.

3.2.3. *Sensitivity analysis*

The sensitivity analysis obtained through Monte Carlo simulations compared the probabilities that environmental impacts under BAU are greater than those under each WR scenario (*Figure E, Supplementary Materials I*). For most categories, such as acidification, climate change, and eutrophication (marine and freshwater), the mean probabilities that BAU ≥ WR_1 or BAU ≥ WR_2 are low, suggesting a high likelihood that WR_1 performs better environmentally (*Table K, Supplementary Materials I*). The analysis illustrates that toxicity related categories (freshwater and carcinogenic and non-carcinogenic human toxicity) show larger coefficient of variations pointing to high uncertainty in the estimates.

3.3. *Future scenarios for water reuse diffusion in 2050*

3.3.1. *Key drivers of change*

The results of the two rounds of e-Delphi survey shows the five key external drivers influencing the adoption of non-conventional water resources in the Mediterranean: *water scarcity*, *reuse costs*, *public awareness, financial incentives*, and *communication strategies* (as shown in the scores of Fig. 3). Water scarcity, especially under climate stress and migration (Megatrend: aggravating resource scarcity), was seen as a major pressure point likely to intensify competition among sectors like agriculture and tourism. High reuse costs, particularly burdensome for farmers, particularly where freshwater remains underpriced, were also flagged as a barrier. Experts cited limited public awareness, trust, and poor communication between stakeholders as further obstacles. The lack of targeted incentives was viewed as a policy gap, though EU Regulation 2020/741 may help address this. On internal drivers, experts highlighted *bureaucracy*, *profitability*, *water quality*, *technological efficiency*, and *environmental risks*. Regulatory hurdles and high treatment costs—especially for emerging pollutants—limit uptake. Experts recommended integrated, cost-effective solutions and better environmental performance, aligning with the megatrend of accelerating technological change and hyperconnectivity.

3.3.2. *Scenarios logic and storylines*

Based on the drivers and their interlinkages, four future scenarios for the use of non-conventional water resources were developed. While water scarcity is expected to intensify across all scenarios, two key axes define their variation: public *awareness* of reclaimed water and the availability of *financial incentives*. The vertical axis reflects levels of awareness and communication effectiveness. Low awareness is marked by mistrust and poor communication among stakeholders, whereas high awareness results from effective strategies that build confidence in water reuse. The horizontal axis represents the financial landscape, with low incentives and high reuse costs limiting adoption, particularly among farmers. Conversely, high incentives reduce costs, attract investment, and increase farmers' willingness to pay. These two axes structure the four scenarios presented in Fig. 4a, each offering distinct pathways for water reuse uptake based on socio-economic and institutional conditions. Detailed storylines for each scenario are provided in *Table* L, *Supplementary Materials I*.

Fig. 4b illustrates the anticipated timeframes for the realisation of each scenario, as estimated by experts. Three of the five focus groups identified Scenario A (high cost, low awareness) as reflective of the current context. Group 4 considered this scenario to have already occurred in the past, while Group 5 noted that reuse could help address water scarcity. Scenario C (high cost, high awareness) is expected to emerge by 2030, whereas Scenario B (low cost, low awareness) is

Table 4

Life Cycle financial and environmental costs of producing 1 kg of processing tomatoes at farm gate under different water management scenarios. Values in brackets indicate the environmental costs obtained using low and high monetisation factors.

Scenario	Financial Costs (€$_{2023}$/kg)	Climate Change (€$_{2023}$/kg CO_2 eq./kg)	Marine Eutrophication (€$_{2023}$/kg N eq./kg)	Human Toxicity, non-carcinogenic (€$_{2023}$/CTU$_h$/kg)	Water Use (€$_{2023}$/m^{3}water eq./kg)	Environmental Costs (€$_{2023}$/kg)	Total Costs (€$_{2023}$/kg)
BAU	0.14[a]	0.02 (0.01–0.03)	0.01 ([b])	0.02 (0.00–0.09)	0.01 (0.01–0.30)	**0.06** (0.03–0.42)	**0.20** (0.17–0.56)
WR_1	0.18[a]	0.01 (0.01–0.02)	0.01 ([b])	0.02 (0.00–0.07)	0.00 (0.00–0.00)	**0.04** (0.02–0.11)	**0.22** (0.20–0.29)
WR_2	0.15[a]	0.01 (0.01–0.02)	0.01 ([b])	0.02 (0.00–0.09)	0.00 (0.00–0.00)	**0.04** (0.02–0.12)	**0.19** (0.17–0.27)

[a] Adapted from ISMEA Mercati (2024).

[b] Marine eutrophication coefficients do not report low and high monetisation values.

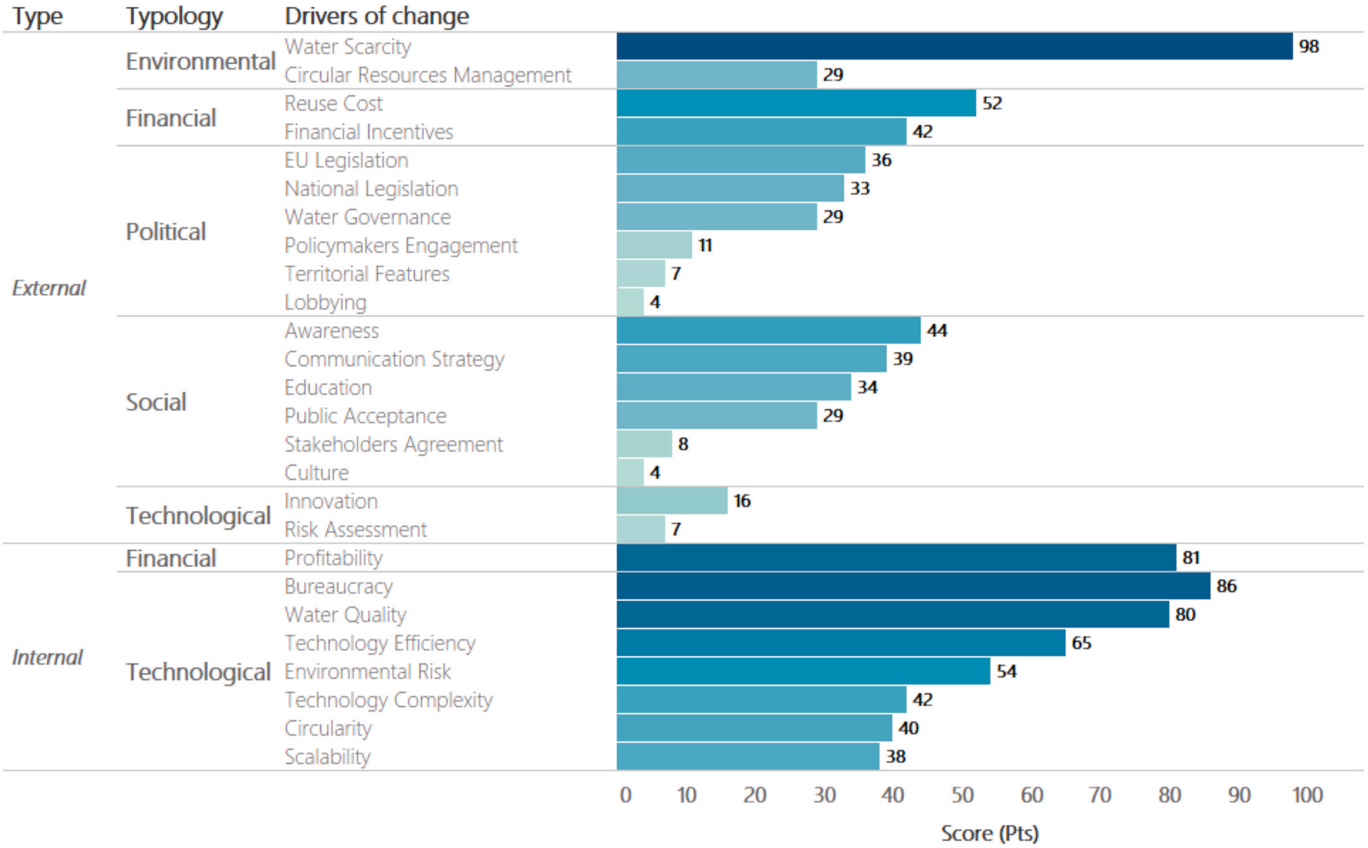

Fig. 3. Scores of the ranked drivers of change identified in the two Delphi e-surveys.

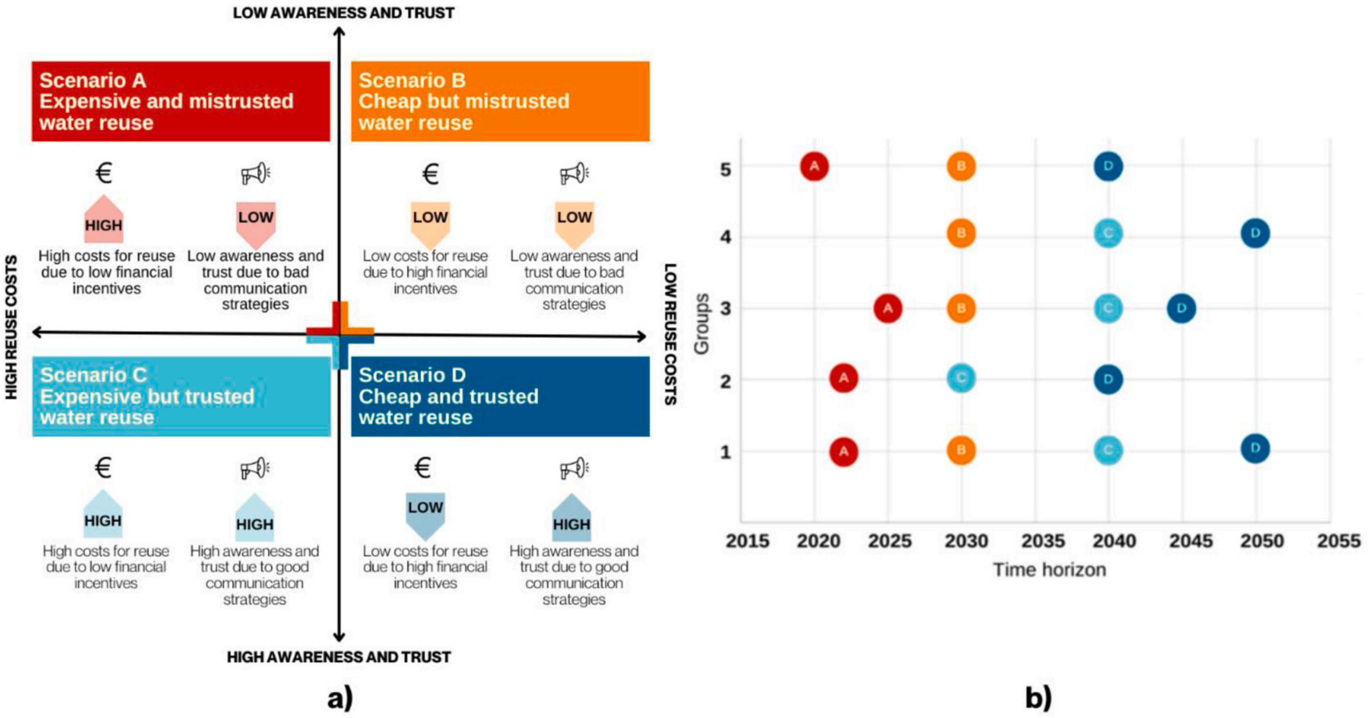

Fig. 4. The four scenarios for the diffusion of non-conventional water resources based on the most influential drivers of change identified (3a) and time horizon in which the scenarios are expected to realise (3 b) (colour should be used for this figure in print). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

projected by three groups to materialise within 20 years. However, Group 3 anticipated its emergence by 2030, while Group 5 regarded it as unlikely due to the energy crisis. All groups agreed that Scenario D (low cost, high awareness) may be realised between 2040 and 2050. It was also identified by Groups 1, 3, and 5 as both the most desirable and likely scenario. However, Group 3 noted that achieving low costs remains a major challenge. Group 2 viewed Scenario A as more probable, though D remained the preferred option. Group 4 considered Scenario C most likely and desirable, judging Scenario D as overly optimistic.

3.3.3. Actions and interventions

Discussions on operationalising the scenarios emphasised economic instruments, institutional leadership, and stakeholder collaboration—particularly with public authorities and farmers—while perspectives varied on the roles of regulation, partnerships, and innovation in advancing water reuse. Table 5 summarises the results following the three policy approaches suggested by Ejelöv et al. (2022). The most favoured policy actions included pricing regulations for freshwater and wastewater (endorsed by four groups), integrating water reuse into agricultural best practices (three groups), and education and awareness campaigns (three groups). Stakeholder mapping identified Public Authorities (n = 18) and Farmers/Farmer Cooperatives (n = 12) as most critical, with less frequent mentions of Private Sector (n = 8), Academia/Research (n = 7), Consumers/Citizens (n = 4), and NGOs (n = 2). Policy strategies varied: all groups targeted public authorities, while three (Groups 1, 2, and 4) also prioritised farmer engagement. Group 3 proposed a strict legislative approach enforcing reuse in agriculture, whereas Group 5 favoured a broader strategy centred on private sector and academic collaboration.

4. Discussion

4.1. Summary of evidence

Pilot-scale analysis unveiled possible environmental and financial hotspots of the innovative technologies for water reuse. The UASB process has shown significant environmental advantages, particularly due to biogas production, which can offset environmental impacts in water reuse projects by enhancing system circularity and economic value (Giakoumis et al., 2020). Given that energy consumption is a major environmental hotspot in WWTPs, integrating energy loops, such as biogas recovery, can mitigate overall impacts (Foglia et al., 2021). The UASB process also offers lower operational costs, supporting its application in smaller-scale WWTPs (*Table J, Supplementary Materials I*). Aerated constructed wetlands (ACWs) contribute significantly to energy use due to aeration demands. While emissions of methane and nitrous oxide are impactful at the pilot scale (Resende et al., 2019) scaling up to 5000 PE suggests potential for improved emissions efficiency per cubic metre of treated water. However, aeration processes and the need for larger compressors introduce substantial impacts (*Figure D, Supplementary Materials I*), though intermittent aeration seemed promised in smaller systems (Mancuso et al., 2024). Further optimisation is necessary to balance emissions, energy consumption and treatment performance at larger scale.

Table 5
Policy interventions and key target stakeholders identified by water experts to implement the most desirable scenarios.

Policy Approach[a]	Policy Intervention (push/pull)	Nr. of groups selecting the intervention	Nr. of groups selecting the target stakeholders					
			Public Authorities	Farmers and Farmers Cooperatives	Private Sector	Academia and Research Centres	Consumers and Citizens	NGOs
Push	Develop guidelines on good practices and success stories on WR	**1**	1	1		1		
	Enforce rules on freshwater and wastewater pricing	**4**	4	2			1	
	Enforce freshwater abstraction tariffs	**1**	1	1			1	
	Improve compliance rates on wastewater treatment for public long-term investment planning	**1**	1					
	Increase monitoring for freshwater used for irrigation	**1**	1	1				
	Investment in R&D to boost technology efficiency	**2**			2	1		
	Payment for Ecosystem Services schemes for farmers	**1**	1	1				
	Integrate WR in fertilisation guidelines and legislation	**1**	1					
	Integrate WR in guidelines for best practices on agriculture	**2**	2	2				
Pull	Initiatives to support market uptake of water reuse technologies	**2**	1		1	1		
	Develop voluntary ecolabels and GPP criteria for WR	**2**	1		1	1		
	Promote cooperation between water supply and sanitation stakeholders	**2**	1	1	1			
	Promote industrial symbiosis	**1**			1			
	Promote integration of water footprint in voluntary environmental product declaration (EDP)	**1**	1		1			
	Support innovation in reclamation technologies and the up skilling of professionals in the water sector	**1**		1		1		
Inform	Implement education and awareness campaign	**3**	1	1	1	1	1	2
	Promote water citizen science for wastewater monitoring	**1**	1			1	1	
Total			**18**	**12**	**8**	**7**	**4**	**2**

[a] Based on the taxonomy by Ejelöv et al. (2022).

MIPs have been found to be resource-intensive at the pilot scale, nonetheless its technology upscaling indicates no notable differences in environmental impacts, largely due to the regeneration capacity of their substrate (Parlapiano et al., 2024). Further, they proved to decrease impacts on non-carcinogenic human toxicity compared to conventional WW treatment in BAU scenario (Fig. 2). Emerging pollutants are not adequately addressed by existing WWTP technologies, particularly those associated with the overuse of anti-inflammatory drugs, which have been shown to exhibit high toxicity to both human health and ecosystems (Samal et al., 2022). From a financial perspective, MIPs have proven to be costly compared to conventional WW treatment (BAU Scenario), even when environmental impacts are monetised (Table 4). Indeed, as MIPs serve as an additional treatment method - supplementing, rather than replacing conventional tertiary treatment (*e.g.* UV) in water reuse systems - they inevitably contribute to increased operational costs. While other studies have proven their adaptability to treat sensitive sites (*e.g.* hospitals) (Yang et al., 2022), their upscaling hypothesis suggests further evaluation of health costs and the technology downscaling to smaller capacities.

When simulating a full-scale scenario in which the proposed technologies are implemented, both water reuse scenarios demonstrate improvements in environmental performance, particularly with respect to water consumption (Fig. 2). These findings are consistent with existing studies, which have shown that water reuse schemes can effectively reduce impacts related to eutrophication (Canaj et al., 2021; Moretti et al., 2019), water use (Moretti et al., 2019), and climate change (Miller-Robbie et al., 2017). While these studies also identified various trade-offs, direct comparisons are limited due to differing assumptions underpinning scenario development. Also, regional differences in infrastructure, regulatory frameworks, and climate may substantially influence both the technical and economic performance of these technologies in different Mediterranean countries. Kalboussi et al. (2022) and Maeseele and Roux (2021) highlighted how much water management impacts are context-dependent, influenced by site-specific environmental and location-specific factors, which further complicates cross-study comparisons, especially in the present study, where the upscaling of pilot technologies was based on assumptions.

Unlike much of the existing literature, this study assessed results in terms of absolute environmental sustainability. While the water reuse scenarios improved environmental performance relative to the baseline, the findings indicate that considerable progress is still required to ensure crop production remains within planetary boundaries. Fig. 2 illustrates how close conventional technologies are to surpass the planetary boundary for water use, highlighting the potential of water reuse technologies to support more sustainable production systems. Consistently, Bjørn, Sim et al. (2020) reported strong variability in irrigation water consumption across 27 watersheds worldwide and showed that tomato production frequently exceeded the safe operating space for freshwater use, underscoring the challenges of achieving sustainability in water-intensive crops. This is particularly relevant considering increasing pressure to water resources due to agricultural use (Flörke et al., 2018) in regions affected by freshwater scarcity such as the Mediterranean (Macias et al., 2025). Exceedances in the other impact categories are largely attributable to upstream processes, particularly fertiliser and pesticide production and application, which contribute substantially to emissions and pollutant loads. For example, freshwater ecotoxicity is closely linked to the use of plant protection products, while climate change and eutrophication impacts are mainly driven by fertiliser-related emissions and energy consumption across the supply chain. Strengthening the nexus between water reuse and other resource recovery (*e.g.* fertilisers and energy) offers opportunities to mitigate exceedances in these categories (Kehrein et al., 2020; Mo and Zhang, 2013).

In terms of direct costs, the water reuse scenario without MIPs is more expensive than the conventional system, with irrigation costs increasing from 0.51 €/m^3 to 0.79 €/m^3, resulting in an additional cost of 500 €/ha in the WR_1 scenario. This leads to a modest increase of approximately 5 % in the cost of tomato production (from 0.14 to 0.15 €/kg). However, in terms of environmental costs, the BAU proves significantly more expensive—by nearly 50 %—compared to the WR_1 and WR_2 scenarios (4692 vs 3128 €/ha). These findings highlight the importance of considering environmental externalities into cost assessments and contribute to the ongoing debate on freshwater pricing and the economics of water reuse, especially in context in which water scarcity is relevant (Zetland, 2021). This was also reflected in the stakeholder focus group discussions (Table 5), which highlighted the importance of freshwater and wastewater pricing. Nonetheless, local environmental conditions, institutional frameworks, and the technical and economic characteristics of reuse systems are also critical factors that should inform decisions on pricing recycled water (Fagundes and Marques, 2023).

4.2. *Limits of this research*

A key limitation of this study concerns the LCA reliance on average datasets (*e.g.*, Ecoinvent Database), which may not fully capture regional variability in detail. However, this is common constraint in LCA practices (Hellweg and Milà i Canals, 2014) and effort were made to mitigate when selecting country-specific processes whenever available. This approach ensured methodological consistency but inevitably reduces the representativeness of certain flows, particularly where regional deviate from European or global averages. The absence of more spatially resolved life cycle inventory data introduces uncertainty into the results, which should be considered when interpreting the findings. In addition, while pilot-scale data were collected through interviews, the upscaling process based on assumptions and estimates for full-scale scenario development that could not reflect reality. Tomato cultivation conditions can be affected by environmental (*e.g.*, soil, climate) and biological factors (*e.g.*, plant species) and although these conditions were considered identical in all the scenarios, they can affect fertilisers savings (estimated using experimental trials' results) and the whole variability of the scenario. Furthermore, the scalability of these findings to other Mediterranean contexts beyond Italy should be interpreted with caution reinforcing the need for regionalised assessments. Finally, LCA also lacks robust characterisation factors for biological water parameters (*e.g.*, *E. coli*, COD), limiting differentiation in discharge impacts and potentially overlooking human health and environmental risks.

The absolute sustainability assessment, based on planetary boundaries, may not fully highlight the most urgent environmental hotspots. Economic allocation, though commonly used, has limitations due to mismatched temporal and spatial data (*e.g.*, boundaries set in 2020 vs. current prices/GDP). Future refinements could involve expert-based adjustments to better represent regional pressures. Certain social impacts associated with water reuse, as discussed in Opher et al. (2019), were not addressed in this study due to a lack of data.

Monetisation methods display limitations (Brooks and Diaz-Bonilla, 2025) and remain subject to inconsistencies inherent in their novelty (Galgani et al., 2021) and results should be interpreted with caution. While they help assess hidden costs, they do not reflect potential environmental or human health benefits. Furthermore, the application of EU-wide PEF-compatible valuation factors represents a constraint, as no regionalised coefficients are currently available. Although this ensures methodological consistency and comparability with other studies, it may limit the sensitivity of the results to local socio-economic conditions and Italian context. Finally, limited stakeholder representation in some categories (e.g. farmers and civil society) may influence the interpretation of findings and the robustness of the scenarios developed. A greater presence of academia and the public sector is not unexpected in the context of emerging technologies, although it inevitably creates an imbalance in perspectives. Strengthening the representation of under-represented groups is a common challenge in foresight studies (Hebinck et al., 2018), particularly when applied to novel technologies. Future research should prioritise broader engagement to ensure that water management scenarios are more representative of real-world conditions and consistent with the findings of this foresight exercise itself, which underscored the importance of engage wider society.

4.3. Research and policy implications

This study combined a sustainability analysis and qualitative expert-led foresight to inform long-term policy strategies for the Mediterranean region. By identifying sustainability hotspots and future drivers of change for water reuse diffusion, it highlights both research needs and actionable pathways for policy.

Experts confirmed that escalating water scarcity and the cost of reclaimed water are pivotal in determining market viability (Fagundes and Marques, 2023). Given that reuse costs are determined by technological efficiency, water quality requirements, and administrative burdens, future research should focus on developing cost-effective and scalable solutions. From a policy perspective, promoting integrated strategies for resource management and recovery—extending beyond irrigation to whole-farm systems—represents a promising approach to reducing the multiple environmental burdens of agriculture (see Fig. 2). Such strategies can help align water reuse with broader sustainability objectives, supporting both resilience in farming systems and regional policy.

While regulatory frameworks such as ISO 16075:2020 and EU Regulation 2020/741 provide essential standards by setting harmonised water quality classes, mandating risk management plans, and enhancing transparency, complementary policy interventions remain necessary. Although the Regulation addresses some of the barriers identified in this study, particularly around public trust and safety, it does not directly resolve the economic challenges of advanced treatment and monitoring. Policy intervention should therefore be grounded in territorial cost-benefit assessments to clarify cost distribution (Hadjimichael et al., 2016) and ensure broader socio-economic benefits (Expósito et al., 2024). Further, future studies should explore water reuse projects scalability through multi-country analyses to account for diverse infrastructural, policy, and climatic conditions across the Mediterranean. Public awareness and social acceptance remain major barriers, with concerns about water quality, mistrust, and feelings of disgust limiting uptake (Nkhoma et al., 2021; Ricart and Rico, 2019). This highlights the importance of behavioural research and interventions (Smith et al., 2018), particularly those directed at farmers as key decision-makers.

Scenario analysis revealed that the most desirable future involves strong financial incentives, reliable technology, and high public trust—achievable not only through pricing reforms but also through nudging strategies and awareness campaigns. Financial incentives have been shown the potential to play a critical role in enabling the adoption of wastewater reuse in agriculture (Cagno et al., 2022; Giannoccaro et al., 2022). For instance, in Cyprus, nearly 80 % of tertiary treated wastewater is reused for irrigation, supported by state investment in infrastructure and its integration into national water resource management plans (Christou et al., 2024). On the other hand, more initiatives to engage citizens and civil society can increase trust and acceptability, for instance, by establishing living labs and co-designing activities, such as water-oriented living labs (Water Europe, 2023) or citizens science initiative for water quality monitoring (Loghmani-Khouzani et al., 2024).

This study used environmental and financial hotspots identified to inform a foresight exercise exploring future water reuse scenarios in the Mediterranean. This approach illustrates how LCT can be more effectively integrated into policy development. While LCA supports decision-making (Sala et al., 2021), further studies are needed to validate its role in forward-looking LCA types, such as consequential or prospective (Cucurachi et al., 2022). Future research should explore this integration to assess emerging technologies and support circular economy strategies and sustainable policy frameworks (De Laurentiis et al., 2024).

5. Conclusions

This study evaluated the long-term sustainability of alternative water management scenarios in Mediterranean agriculture through a case study in Emilia-Romagna, Italy, focusing on tomato production. The LCA demonstrated that reuse scenarios can reduce environmental impacts, particularly in water footprint and fertiliser demand relative to conventional irrigation, though impacts such as eutrophication and ecotoxicity still remained above planetary boundaries thresholds, illustrating how water reuse has the opportunity to promote integrated strategies for resource management and recovery within whole farming systems. The LCC analysis revealed higher direct costs for reused water, but once environmental externalities were considered, conventional freshwater irrigation proved more costly in the long term, underscoring the value of integrating environmental costs into water pricing.

Expert foresight highlighted cost and investment needs as the main barriers, alongside limited public awareness, pointing to the importance of financial incentives, reliable technologies, and communication strategies. Overall, the study demonstrates that water reuse can deliver tangible environmental and economic benefits, for instance, in Italian tomato cultivation, while identifying the policy and social conditions necessary for wider Mediterranean adoption by 2050.

CRediT authorship contribution statement

Valentina Guerrieri: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Simone Amadori:** Writing – original draft, Formal analysis, Data curation. **Laura García-Herrero:** Writing – original draft, Validation, Methodology, Conceptualization. **Rémi Declercq:** Writing – review & editing, Validation, Formal analysis, Data curation, Conceptualization. **Matteo Vittuari:** Writing – review & editing, Validation, Supervision, Resources, Conceptualization.

Ethical approval

The research has been conducted within *Fit4reuse - Safe and Sustainable Solutions for The Integrated Use of Non-Conventional Water Resources in The Mediterranean Agricultural Sector*, funded by the European Union's Horizon 2020 Prima programme under Grant Agreement No. 1823. The research was approved by the project coordination and the project was subject to rigorous ethical review, as per institutional requirements and in accordance with the European Union data protection law (GDPR).

Data included in this study were collected complying with European regulation on protection (GDPR). Written informed consent was obtained at the moment of the interview for the Delphi e-surveys, while oral consent was obtained for the focus groups. Respondent provided consent to participate in the study, to use of data and to publication. All participants have been fully informed that their anonymity is assured, why the research is being conducted, how their data will be utilised, and if there are any risks to their participation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.146827.

Data availability

Data will be made available on request.

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