Journal of Environmental Management 384 (2025) 125481

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Worldwide replicability of alternative water recovery technologies to close water loops in decentralised populations

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A R T I C L E I N F O

Keywords:
Decentralised systems
Feasibility assessment
Replicability
Water reuse
Water scarcity

A B S T R A C T

Decentralised systems to recover alternative sources of water (wastewater, rainwater, and seawater) can reduce water scarcity in rural areas by closing water loops while improving the local economy. However, their implementation commonly faces difficulties owing to social, legislative, technical, and economic barriers that must be assessed in local contexts. In this study, the implementation of six decentralised solutions (DCS) that were previously tested to recover water and other products was evaluated at 26 replication sites worldwide. Small, isolated locations were considered for site selection. They generally have scarce water resources and/or inappropriate water sanitation systems, and a high dependency on external regions. A quantitative feasibility assessment methodology (QFAM) developed in a previous study was used to evaluate the potential implementation of the DCS by quantifying relevant data regarding social, legislative, technical, and economic factors collected from the sites.

From the results obtained in the overall assessment, the sites could be divided into two main groups: European sites that showed many similarities, especially in terms of common legal frameworks ruled by EU directives, and non-European sites that showed higher variations in local specificities. Most EU replicability sites showed high feasibility scores; however, for non-European sites, the results were distributed between high and medium feasibility scores. High scores were significantly influenced by high social and legislative feasibility assessments obtained at most sites. However, a general lack of understanding of the specificities of decentralised systems in local authorities and administrations was detected, which can be a significant barrier. Technical and economic assessments sometimes showed medium or low scores owing to certain limitations in the production of some circular products and the lack of financial instruments at some sites to reduce the initial investment for the implementation of DCS.

1. Introduction

Currently, two billion people have no access to safe and clean drinking water (WASH, 2022). In addition, factors such as climate change effects, population growth, changes in consumption patterns, water pollution, limited spread of circular practices, suboptimal water management and inadequate support from governance and financial schemes worsen water scarcity issues (Foglia et al., 2023). Conventional water resources, such as freshwater from rivers, lakes, and groundwater reservoirs, are not sufficient to satisfy the growing water demands. Therefore, it is essential to identify alternative sources of water such as rainwater, runoff, domestic wastewater, and seawater. These non-conventional water sources can be used to reduce water scarcity, especially in arid and isolated regions, while implementing a circular water economy and closing water loops (Hussain et al., 2019; Jarimi et al., 2020; Mainardis et al., 2022; Slater et al., 2020). The collection of rainwater and the direct reuse of wastewater for irrigation are practices that have been traditionally used, especially in developing countries and rural areas (Adegoke et al., 2018; Ghodsi et al., 2023). However, these practices are sometimes carried out without appropriate health and safety measures, resulting in diffuse pollution and other problems for the local population and the environment (Cipolletta et al., 2021; Sun et al., 2024).

Modern decentralised systems can be used to collect, treat, and

This article is part of a special issue entitled: Circular Economy published in Journal of Environmental Management.

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https://doi.org/10.1016/j.jenvman.2025.125481
Received 29 February 2024; Received in revised form 11 April 2025; Accepted 20 April 2025
Available online 29 April 2025

recover alternative water sources in isolated regions by installing efficient, low-carbon, circular water-based solutions (Al-Qawasmi, 2021; Alresheedi et al., 2023). Apart from reclaimed water, which can be used for irrigation/fertigation purposes (Chojnacka et al., 2020), DCS can recover other valuable by-products such as biogas and compost. However, practical implementations of decentralised systems are often scarce (Cipolletta et al., 2021; Mankad and Tapsuwan, 2011). One reason for this is that most political decisions on water management are made considering large populations, often underestimating the relevant contributions of pollutants coming from mismanaged decentralised wastewater systems. In fact, the proposal of a new European Wastewater Treatment Directive (WWTD) (European Parliament, 2024) considers only populations of over 1,000 inhabitants, leaving smaller populations out of the obligation to treat their wastewater. However, diffuse pollution from the decentralised regions of the EU accounted for 11 % of the total pollution originating from treated and untreated sewage (Pistocchi et al., 2019). Therefore, this is not a minor issue. Another issue is related to the scarce knowledge of technicians and decision makers on the potential benefits of decentralised systems for isolated areas as well as their specificities (Cipolletta et al., 2021). Applying the same technical principles and legal requirements to both centralised and decentralised populations in every context can significantly increase their management costs in isolated areas, thus decreasing the feasibility of alternative water recovery systems (Cipolletta et al., 2021). Apart from economic limitations, there have been many legal and social gaps that can hinder the development of decentralised water recovery systems in isolated regions, such as limited public acceptance, and legal and cultural barriers (Leigh and Lee, 2019; Radini et al., 2023; Trapp et al., 2017). All these factors must be detected and evaluated; however, they generally depend on the local context (Kambanou and Sakao, 2020). Different local conditions (socio-economic, cultural, geographic, and legal) require different water management and governance practices that must be assessed (Bichai et al., 2018; Carvalho et al., 2022; Gómez-Román et al., 2020). However, this task is challenging and time-consuming. It also requires specific knowledge of the local situation (e.g. socioeconomic context, culture, and local needs). To simplify the evaluation process, it is necessary to standardise the assessment of decentralised systems globally and comprehensively. In this respect, multi-criteria decision analysis (MCDA) is useful. The MCDA is a well-known methodology that combines qualitative and quantitative information from relevant stakeholders related to social, economic, environmental, and institutional aspects (Jiménez-Ariza et al., 2023; Kandakoglu et al., 2019; Ram and Irfan, 2021; Sahabuddin and Khan, 2021). The factors selected in MCDA were numerically quantified, indicating their relative importance by ranking the alternatives assessed according to the specific factors selected. Previous studies have used MCDA methodologies to assess environmental solutions and strategies. For instance, Antunes et al. (2017) included environmental integrity, economic resilience, social well-being, and governmental practices as basic components of a holistic assessment of different agricultural systems, whereas Johnson (2018) demonstrated the benefits of local expertise in small-scale applications. Wojcik-Madej et al. (2025) used global standards from the International Union for Conservation of Nature (IUCN), effectiveness level, challenge orientation, social preferences, and implementation feasibility to select the most suitable nature-based solutions for implementation in the urban area of Lublin (Poland). However, the water sector is highly complex as it is transversal and applies to multiple levels of governance (Cipolletta et al., 2021; Nika et al., 2020).

Some authors have highlighted the importance of using the multi-criteria analysis of decentralised water recovery systems in global contexts to reduce barriers to water reuse and encourage local administrations and users to implement them. For example, Bichai et al. (2018) used a framework for analysing a multilevel innovation system (FAMIS) to evaluate cases from Australia, the United Emirates, and Jordan. Moreover, Domènech et al. (2013) performed a social multi-criteria evaluation in the Metropolitan Area of Barcelona city (Spain) to explore the compatibility of non-conventional water supply technologies (centralised and decentralised) with degrowth principles. Furthermore, Cole et al. (2017) used MCDA to evaluate four alternative strategies for reusing water for non-potable municipal purposes in comparison to conventional water supply systems, whereas Zheng et al. (2016) developed a scenario-based MCDA framework to plan wastewater infrastructure under uncertainty. However, the information provided by these studies is generally based on theoretical concepts or limited site-specific qualitative information, which is difficult to compare with other socioeconomic contexts. Hence, previous reports are insufficient to comprehensively and globally understand water scarcity issues. This study aimed to overcome this limitation by assessing the feasibility of replicating six circular water DCS in 26 water-scarce isolated regions distributed globally using a quantitative feasibility assessment methodology (QFAM) based on MCDA. Both the DCS (Section 2.1) and QFAM (Section 2.3) were developed and tested in previous studies conducted within the framework of the HYDROUSA project (HYDROUSA, 2024).

In addition to assessing the feasibility of DCS technologies with the goal of maximising their potential implementation at local sites, the QFAM methodology enabled us to obtain comprehensive information (at the global level) on the status of water scarcity regarding social, legislative, technical, and economic factors, which were evaluated in this study. This information is highly relevant for water stakeholders from different perspectives. It can help technological developers and scientists better understand local needs and adapt their innovation activities to their requirements. The results could also be useful for decision-makers in detecting legal and social barriers and gaps that could be overcome by following certain guidelines and recommendations. Moreover, financial information could be used by investors and end users with information to preliminarily evaluate the economic profitability of the solutions as well as potential economic strategies to be adopted for the investment. The results of this study also enabled the evaluation of specific similarities and differences between the international decentralised regions; detected feasible locations to implement the DCS (in theory); found gaps and/or barriers in the local sites regarding social, legislative, technical, and economic factors; and recognised the regions where those gaps or barriers would be complex, facilitating consideration of alternative approaches.

2. Material and methods

2.1. Decentralised solutions (DCS)

Six DCS used to recover alternative water sources were assessed in this study. These systems, known as DCS 1–6 have been implemented and tested on three Greek islands (Lesvos, Mykonos, and Tinos) within the framework of the HYDROUSA H2020-project, showing promising results in terms of water recovery capacity, production of bioproducts, low energy consumption, and environmental impacts, as well as the potential to improve the local economy (HYDROUSA, 2024).

DCS-1 is a sewage treatment system that combines anaerobic processes with constructed wetlands and disinfection, with the possibility of recovering reclaimed water for irrigation and/or fertigation). DCS-2 is an agroforestry system that can use the nutrient-rich water from DCS-1 to cultivate edible and non-edible trees, shrubs, and herbs that can properly adapt to local climate conditions, thereby helping to retain soil humidity and increase its biodiversity (Nika et al., 2022). DCS-3 is an innovative rainwater harvesting system which allows the storage of the appropriate amount of rainwater to irrigate croplands in a self-sufficient manner, that is, without external sources of water. DCS-3 is also characterised by its visual adaptation to the local site and simplicity, which enables minimal reduction in construction work (Vasilakos et al., 2023). DCS-4 is a rainwater harvesting system that can be applied to domestic residences to reclaim water for multiple purposes such as irrigation, aquifer recharge or non-potable domestic uses (Vasilakos et al., 2021).

DCS-5 is a desalination system powered by solar energy (renewable energy) coupled with saltwater evaporation (Zecca and Bianciardi, 2022). Desalinated water was used to irrigate a greenhouse planted with tropical fruits. DCS-6 consists of an agro-ecotourism facility (www.tinosecolodge.gr), which is a form of tourism that combines ecotourism and agrotourism, involving tourist participation in sustainable farming, learning about local agricultural practices, and moving towards water, energy, and food self-sufficiency (Ghafourian et al., 2022).

These solutions were selected as examples of potential water recovery solutions for decentralised regions; however, the approach of this study could be extrapolated to analogous solutions. It must be noted that for assessing the feasibility of implementing the DCS in the replication sites, the design and operating conditions of the DCS were theoretically adapted by extrapolating their main key performance indicators (KPIs).

2.2. Replication sites

A total of 26 international sites were chosen to assess the feasibility of replicating the DCS solutions. These sites are distributed worldwide and are comprised of 13 European and 13 non-European sites. Sites were selected with the aim of covering all continents and diverse scenarios (Fig. 1), while also assuring the participation of local stakeholders. As the DCS were tested on the Greek islands, more focus was placed on replicating the solutions at European sites, as some similarities are maintained between EU members, especially in their legislative framework, which is generally normalised by EU regulations. The sites were selected as representative decentralised locations where issues such as isolation, limited water resources, excessive groundwater extraction, conflicts between economic sectors (agriculture, tourism, household activities, livestock, and industry), limited efficiency of sanitation systems, and high dependency on metropolitan areas were common challenges.

2.3. Replication of DCS and feasibility assessment methodology

The feasibility assessment of replicating the DCS was structured in two main steps: i) the selection of the most appropriate DCS to satisfy the local needs, and ii) the assessment of the selected DCS according to a standardised QFAM based on MCDA(Huang et al., 2011; Sahabuddin and Khan, 2021). To standardise the information to be collected in each site, a "Replication plan" (RP) was developed. This plan details the data necessary from local sites to replicate the DCS and describes the QFAM to quantify this information.

2.3.1. Selection of DCS

To select the DCS, information was required in the following issues: i) technical description of the decentralised area to replicate the DCS; ii) environmental constraints; and iii) local environmental and water-related plans and strategies in force at sites that could favour or

Fig. 1. Replication sites.

hinder DCS replication.

The technical description of the area to be replicated should contain these main elements: extension of the area (available m^2 for DCS implementation); geological and orographic characteristics (e.g. slopes and altitude); climatic conditions (e.g. solar irradiation, temperatures, rainfalls, etc.); description of nearby existing infrastructures (e.g. wastewater treatment plant, sewer systems, industrial complex, etc.), characteristics of the water to be treated or collected (physic-chemical parameters). Once the area for the replication site was identified, the possible environmental constraints was assessed in terms of possible restrictions due to local legislation (e.g. the presence of sensitive or protected water bodies, specific noise, vibration and dust emission levels); geological constraints to ensure a good water regime in terms of flood prevention and land stability; forestry restrictions for the protection and conservation of the forests to ensure a high quality of life and biodiversity; constraints related to the protection of water bodies ecological status against pollution; natural/wildlife constraints for the protection of ecological, geological, biological and aesthetic values (e.g. natural parks and protected areas). With respect to the list of local environmental and water-related plans, information was collected on: governance level of the plans (national, regional and/or local levels); description of what the plan includes; targets and constrains for the site; qualitative evaluation, i.e., an indication whether the plans or targets are completely in line, not clearly stated, or against the objectives of the DCS.

To collect this data, local stakeholders were contacted (Table S1). To standardise the information collected, templates containing explanation on the type of data needed were shared with them. These templates were reported in Fatone et al. (2020). Moreover, guidelines were provided to the local stakeholders on the potential benefits that each DCS could provide to the local site, as well as on their potential limitations. Considering all this information, the local stakeholders decided the DCS to be replicated according to their local needs and specificities. The DCS selected, the main water and environmental issues, and the expected benefits from the implemented solutions are described in Table 1 (extended information in Table S2).

2.3.2. Quantitative feasibility assessment methodology

The QFAM used in this study adapted the holistic assessment reported by Antunes et al. (2017), whose elements for assessing the long-term feasibility of DCS were drawn based on resource efficiency, social inclusion, resilience, environmental protection, and economic benefits. These elements were incorporated into QFAM by assessing the technical, economic, social, and political factors (Marleni et al., 2020; Meerholz and Brent, 2012) relevant in the selected geographical locations. To select the relevant factors and sub-criteria to be included in the QFAM, as well as their relative weighting in the final score, multidisciplinary approach was required (Saarikoski et al., 2016). In this respect, contributions from key stakeholders (relevant international technicians, academics, authorities, and other local stakeholders) were collected during online participatory meetings and dialogues with multidisciplinary groups of experts. Previous expertise from the authors, as well as information from literature (Antunes et al., 2017; Cipolletta et al., 2021; Horton et al., 2016; Howes et al., 2017; Romano and Akhmouch, 2019) was also used. The main sub-criteria selected for each factor and their relative weighting scores were as follows:

- **Social** sub-criteria (Ssc): Ssc-1: Stakeholder (SH) and public participation (20/100); Ssc-2: Training and qualifications (16/100); Ssc-3: Public information programmes (16/100); Ssc-4: Monitoring systems (16/100); Ssc-5: Research projects (16/100); Ssc-6: Decentralised systems/ecosystem services (16/100).
- **Legislative** sub-criteria (Lsc): Lsc-1: National/regional laws or regulations (12/100); Lsc-2: National/regional strategies and action plans (11/100); Lsc-3: Planning/zoning (11/100); Lsc-4: Targets (11/100); Lsc-5: Standardisation of processes and products (11/100); Lsc-6: Bans (11/100); Lsc-7: Permits/quotas (11/100); Lsc-8: Environmental impact assessment (11/100); Lsc-9: Green Public Procurement (GPP) (11/100).
- **Technical** sub-criteria were calculated by comparing the production of alternative circular products at the replication sites (estimation) with the production in the DCS tested in Greece (KPIs, see Table S5). As the circular products obtained in each DCS were different, the sub-criteria differed for each solution: DCS-1+2 (reclaimed water, compost, and energy from biogas), DCS-3 (rainwater collected), DCS-4 (rainwater + runoff collected; water stored in the aquifer; drinking water production), DCS-5 (rainwater collected; freshwater produced; salt produced), and DCS-6 (drinking water from vapour; harvested rainwater and reclaimed water from greywater). Technical scoring was calculated as the average value of all the circular products of each DCS.
- **Economic** feasibility was evaluated through the return on investment (ROI) of DCS implementation, which was calculated by estimating economic costs, that is, capital expenditures (CAPEX) and operational expenditures (OPEX), as well as benefits. At the replication sites where financial instruments were detected (confidential data), these public and/or private sources of funding were considered in the assessment, thereby reducing the total CAPEX. Economic scoring was calculated using linear extrapolation, considering the maximum score (100/100) for the 0-year ROI and the minimum score (0/100) for the 18-year ROI.

To collect the data in the local sites, similar procedure to the selection of DCS (Section 2.3.1) was done. Local stakeholders were provided with templates containing instructions to complete all the qualitative information necessary to carry out the quantitative feasibility assessment. This information is provided in Section S2, which summarises the methodology implemented in a previous study (Fatone et al., 2020).

From the information provided by the local stakeholders, the sub-criteria were quantified by the authors according to the defined factors (Tables S3–S5), obtaining scores between 0 and 100 for each factor (social, legislative, technical and economic). To obtain the overall feasibility assessment score, 30 % weighting was applied to both social and legislative feasibility, whereas the weighting for technical and economic feasibility was 20 % each. For all specific and overall values, feasibility scores in the range of 0–49 were considered low, 50-69–considered as medium, whereas 70-89–considered as high. When the scores were over 90, the feasibility was considered very high.

3. Results

The results obtained from the QFAM enabled the quantification of all data collected from the sites (data not shown owing to confidentiality), thus simplifying their evaluation by obtaining single scores for each factor as well as an overall score.

Social aspects were analysed to evaluate the possible influence of the DCS on society, the quality of life of the locals, and the information instruments which currently exist or could be implemented in the replication sites to engage decision-makers and the general public (Table S6). In general, the replication sites (both European and non-European) showed high social feasibility, obtaining scores over 70 in 22 of the 26 sites, with 9 of them having very high scores, that is, over 90 (Fig. 2).

Regulatory instruments at the continental, national, and/or regional levels were analysed regarding the valorisation of circular products obtained by the DCS (Section S3). The goal was to assess whether in-force legislation generally supported or hindered the implementation of DCS. The legislation was checked for the elements listed in Table 2, which differed for each DCS.

The scoring assignments for each replication site are shown in Table S7. The final legislative assessment scores are shown in Fig. 3.

The feasibility score achieved at most replication sites was high

Table 1
Main characteristics of the selected replication sites.

Summary of replication sites					
Site	DCS	Population	Water issues	Environmental issues	Expected benefits from DCS
1. Chamorga (Tenerife, Spain)	DCS 4	37	- No running water. - Isolation. The area has been being partially abandoned. - Loss of economic activities. - No nearby WWTP, nor general sewer system. Risk of contamination of aquifers and environment.	- Area located within the *Anaga Rural Park*. The forest mass (*Laurisilva*) is protected - No prohibitions to collect and use the water. - It is prohibited to discharge toxic and dangerous gases and wastes, solid or viscous residues that clog the pipes, colouring matters, corrosive residues, salty or brackish water.	- High capacity of capturing water from the environment. - Increase the self-sufficiency of the area in terms of water supply. - Increase the awareness about rainwater harvesting. - Plant more intensive crops.
2. Santa Maria (Portugal)	DCS 3	5,408	- High variability of rainfall with high/moderate risks of heavy rainfall and floods. - High tourist activity, especially in July–September. - Water and wastewater services are of high energy consumption and carbon emissions. - The urban sewage system only collects 31 % of the existing houses on the island. Decentralised wastewater systems correspond to more than half of the houses in the island. - The water supply system is under-designed (low storage capacity).	- Santa Maria has 13 areas with the status of Protected Areas. - Santa Maria is also classified as an important paleontological heritage.	- Contribute to obtaining water for irrigation at the point of use, avoiding transportation, and extraction of groundwater. - Improvement of the sustainable management of water and energy. - Contribute to reducing the flood impact by acting as a temporary water storage water.
3. Culatra Island (Portugal)	DCS 4; DCS 5	Around 1000	- Low precipitation (average around 400 mm/y). - Extreme drought seasons. - Challenges in energy efficiency, self-sufficiency, and waste management. High dependency on the mainland. - Sandy soil with low fertility. - Impermeable land. Rainwater runoff is not collectible. The only option are residences' roofs. - Groundwater quality is poor. - Tourism seasonality	- Culatra is situated in the Natural Park of Ria Formosa, which is classified as a special protection zone. - Technologies must comply with applicable noise and vibration standards and regulations (ETA 0701).	- Efficient use of water and water reuse. - Decreasing the energy consumption. - Create new naturalised spaces. - Increase of water availability. - Engagement of the community. - Facing the seasonal fluctuation of water consumption.
4. Formentera (Spain)	DCS 6	12,111	- Lack of natural resources and external dependence. - Moderate to high risk to nitrate pollution. - Marine intrusion. - Scattered urbanisations and touristic urbanisations with a lack of sanitation system in some of these sites. - Sewage sludge management is a relevant problem.	- Formentera is declared as "Sensitive areas to eutrophication". - Special permission is needed to cut the forest. - The seawater is protected because of the Posidonia. - The area is surrounded by "agricultural interest area (AIA)" for vineyards crops.	- The government promotes Formentera as an eco-touristic destination. - Improve self-sufficiency in terms of water, energy, and food production. - Possible rainwater harvesting >1,07 m^3/d.
5. Binissalem (Mallorca, Spain)	DCS 1 + 2	6,773	- High dependance on groundwater (70 % of water). - Consistent infrastructure on medium-large centralised wastewater treatment. – 44,000 houses in Mallorca are estimated to have a lack of sanitation systems. - Existing septic tanks are not well constructed or maintained. - High groundwater pollution by nitrates. - Issues in sewage sludge management. - Excessive energy consumption for water and wastewater transportation - Need to improve the efficiency of water use.	- Restrictions related to the risk of nitrate pollution. - Lack of sanitation systems, and low maintenance of septic tanks. - Water infrastructure shall comply with the law on rustic soil (Law 6/1997 of the Balearic Islands).	- To minimise wastewater discharges into the land at dry weather. - To reduce pressure in groundwater consumption. - To obtain cheaper production of reclaimed water. - To recycle nutrients in agriculture. - The local public water agency considers implementing the DCS in more areas of the island.
6. Cabrera (Spain)	DCS 1 + 2; DCS 4	30 staff members + 89,833 annual visitors	- Lack of a proper wastewater treatment system. - Double isolation (from Mallorca Island and the mainland). - Water is limited on the island. - Marine intrusion.	- "Sensitive areas to eutrophication". - All the island is protected as National Park. - Wastewater discharges from terrestrial areas are banned. - The seaside is polluted due to untreated organic matter. - Strict rules that forbid cutting the forest.	- Increase water availability. - Improve wastewater sanitation. - DCS 2 could be used to grow a forestal habitat for the local fauna. - Provide more water resources for summer requirements

(*continued on next page*)

Table 1 (*continued*)

Summary of replication sites					
Site	DCS	Population	Water issues	Environmental issues	Expected benefits from DCS
					- Increase awareness about rainwater harvesting.
7. Gorgona island (Italy)	DCS 1 + 2	200	- Isolated island. - Limited availability of water resources. - Wastewater treatment facility is currently incomplete with a limited capacity. - Touristic pressures (mainly in summer). - Sewage sludge mismanagement.	- Gorgona belongs to the National Park of the Tuscany archipelago and included in the Natura 2000 Network. - Protected seaside area: 300 m from the coast. - Landscape constraints. - Risk of flooding. - Subjected to acoustic emission limits.	- Water scarcity reduction - Nutrient recovery from wastewater. - Optimisation of sludge management. - Reduction of water pollution. - Opportunity to socially reinclude the inmates of the island.
8. Saint Honorat (France)	DCS 1	45 + 120–349 visits/d	- Limited water resources and high dependency on groundwater. No watercourse exists on the island. - Outdated rainwater harvesting storage tanks and sanitation systems.	- The island has different protected areas and contains cultural heritage buildings protected by the French law. - Specific administrative permits would be needed. - St Honorat applied to the SMILO label of "*Sustainable Island*".	- The DCS can help the abbey to improve its wastewater treatment system. - The abbey is interested in producing nutrients and reused water.
9. Zlarin island (Croatia)	DCS 3	270 (2,000 in summer)	- Low rainfalls in summer (while higher demand). - Frequent droughts. - No running water on the island. - High soil permeability. - Several wells with brackish water on the island.	- The island implements activities towards the sustainable management of its territory. - Zlarin is engaged since 2018 in the "*Sustainable Island*" SMILO Labelling process.	- Increase water supply. - DCS 3 could preserve and promote a valuable cultural and historical tradition, i.e., rainwater reservoirs.
10. Pwales Valley (Malta)	DCS 4 + 5	–	- High water demand and high dependence on groundwater. - Poor qualitative status of groundwater. - The catchment volume is limited.	- Natura 2000 area. - The reservoir should be constructed entirely below ground level (>0.5 m). - Legal limitations to installation photovoltaic panels. - Desalination requires the discharge of brines.	- Increase the amount of water. - Minimise the salt content of groundwater. - High potential of replicating the DCS solutions in different areas of Malta. - Zero-brine discharge approach.
11. Iskra village (Bulgaria)	DCS 1 + 2	1811	- Poor water sources. - Water scarcity periods, especially during summer. - The existing Water Supplying System is old and depreciated, with water losses up to 60 %. - Local water sources are in danger of contamination. - Groundwater extraction produces some hydro-morphological changes. - Diffusive wastewater discharges. - High competition for water between sectors. - Great seasonal irregularity in water consumption. - Scarce centralised wastewater systems Usually, septic pits are used, but they are not controlled. - Non-sustainable agricultural practices.	- High risk of earthquake. - The site falls within the zone for protection of valuable fish species and other water organisms. - Places over zones for protection of groundwaters.	- Decrease the negative anthropological impact on the area. - Reduction of water demand. - Lowering the needs of fertilisers and fossil fuels. - Higher independence of the local municipality.
12. Choletria (Cyprus)	DCS 2	250	- Chronic water scarcity with river runoff reduction of 40 % from 1970. - Precipitations are unevenly distributed and characterised by high seasonality. - Higher water demands. - Reduction of exported products. - Dislocation of regional economies and movements to urban areas. - Economic and societal instability. - Competition for water between sectors.	- Choletria site is close to Natura 2000 Special Protection Areas.	- Conservation of conventional water. - Production of nutrient-rich reclaimed water. - Protection of water resources from nutrient pollution. - Restricting the purchase of imported animal feed. - Reduction of disposal costs. - Reforming and fostering the local economy. - Greenhouse gas emissions reduction and adaptation to climate change.
13. Yenibademli (Turkey)	DCS 1 + 2	1050 (3500–4000 in summer)	- Both villages present water and electrical supply, but wastewaters are discharged to the deep sea. - Water scarcity.	- Protected seaside area: 50 m from the coast. - A construction permission must be obtained, containing a specific archeological report. - Earthquake and flooding risks. - Limitations to treat sludge.	- Removal of pollutants from wastewater. - Production of reclaimed water, biogas and compost from wastewater.

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Table 1 (*continued*)

Site	DCS	Population	Water issues	Environmental issues	Expected benefits from DCS
14. Kaleköy (Turkey)	DCS 6	154 (1000–1500 in summer)		- In Yenibademli, construction in some areas is forbidden. - In Kaleköy, some marine areas are protected.	- Reduction of the consumption of natural resources. - Collection of rainwater and vapour. - Involvement of visitors.
15. Nattoufa (Israel)	DCS1	72,000	- High seasonal fluctuations in wastewater production. - Israeli governments have created highly centralised water management systems. - Water tariffs should enable full-cost recovery in the water sector including costs of conveyance, piping systems and wastewater treatment.	- The selected site is close to Zipori river while the country highly protects the National Parks national reserves and landscape reserves. - Strict rules on sludge managemetn	- Improvement in terms of simplicity, lower capital costs, and less energy consumptions. - Reduction of sludge production.
16. Misilya (Palestine)	DCS2	2,979 1500–2000	- Deterioration of groundwater concerning bacterial pollution. - Future extension of the village is predicted. Accordingly, the production of treated wastewater (effluent) will grow progressively. - Growing dependence on imported water. - High levels of water losses. - Rising costs of service provision, low-cost recovery and low collection rates.	- Pollution of groundwater due to WWTP effluents. - The project plans to store the water treated by for several months during which the quality of the treated water may be degraded.	- Further agricultural development and reduction of the pressure on existing water resources. - Fodder crops, fruit trees and ornamental plants could be irrigated with treated water.
17. El-Wahat Bahariya (Egypt)	DCS2	250,000	- Egypt faces water scarcity crisis. - High contaminant loads in water. - Groundwater contains high concentrations of iron. - No proper wastewater management system exists. - High evapotranspiration.	- Very dry climate and low organic matter concentrations in wastewater. - The water quality limits for reuse are stringent.	- Reuse of drainage water. - Transformation of farming practices. - Using low-tech, low-energy and easy-to-operate solutions that employs local and natural materials.
18. Kerkennah (Tunisia)	DCS3	3,500 + 50 farmers	- Households are not connected to sanitation network - Arboriculture is the main agricultural activity. - The selected site is a natural depression of rainwater accumulation.	- Flood risk, which is related to the presence of mosquitoes. - Decreasing yields have caused the abandonment of agricultural activities.	- Protection of dwellings from flooding and nuisance. - Safeguarding of agricultural activities.
19. Capraia (Italy)	DCS 3	400 (4,000 in summer)	- Rainfalls iare irregularly distributed. - Mountainous area with rocky coasts and caves. - Extremely simple hydrographic profile. - Main water resources consist of several springs and cisterns. - Lack of works in the collection and regulation of water resources. - The drinking water supply system does not reach all areas of the island. - The island depends on biofuel engines for electricity production. - Tourism is an important economic factor. - The sewage network and the WWTP is overseen to be adapted.	- Capraia presents high diversity in the seabed and coasts. - Well-known fauna migratory corridor. - Involved in protected areas (*Tuscan Archipelago National Park*), Natura 2000 (SAC and SPA) and areas restricted for habitat. - Relevant area migratory fauna. - Capraia area is considered a landscape asset, with multiple territories covered by forests, but it has suffered from continuous deforestation and intense pastoral and agriculture activities. - In some areas, the soil is highly degraded.	- Retaining water in rainy periods and provide water in summer. - Reduction of costs and emissions for water transportation. - To overcome water scarcity issues. - To improve the hydrological situation of the island. - DCS 3 could be replicated in other areas of the island.
20. Mezcala (Mexico)	DCS 1 + 2; DCS 3.	5,000	- Rainfalls are not enough to cover water needs. - Wastewater management represents a source of health risk. - Low efficiency in water distribution due to old infrastructure. - Water service is intermittent. - Lack of maintenance of the drainage network. - Some neighborhoods in the community are not connected to the main duct. - Reused water does not receive proper treatment. - Sensitive aquifer nitrate pollution (10–30 mg/L).	- DCS construction requires a permit and a concession from the National Water Commission and license is required. - Risk of flooding.	● - To increase availability of high-quality water for local agriculture. ● - To protect water quality. ● - To reduce diffuse pollution. ● - To change perception of treated wastewater as a resource. - To contribute to the reduction of impacts, to strengthen the circular economy and local capacities, - Example to be replicated in rural areas of Mexico. - To promote healthier food.

(*continued on next page*)

Table 1 (*continued*)

Summary of replication sites					
Site	DCS	Population	Water issues	Environmental issues	Expected benefits from DCS
21. Chancón (Chile)	DCS 1 + 2	–	- Water-scarce region. - The flow in the Cachapoal River has been reduced by around 35 % during the last 5 years. - Socio-economic conflicts related to water uses. - Water supply and sanitation infrastructure are non-existent. - Cachapoal aquifer has been declared as a restricted area for water extractions and has nitrate pollution.	- Chile is one of the most earthquake-active countries in the world.	- To mitigate water scarcity in the area. - To reduce pollution from water sources. - To reduce health issues related to potential faecal water contamination.
22. Xi'an Siyuan University (China)	DCS 1 + 2, DCS 6*	17,000	- Water-scarce region with no other rivers or lakes nearby. - WWTP is undersized during the academic year and with insufficient carbon sources on holidays. - Intensive pump power is needed to overcome the elevation difference in tap water supply pipelines.	- Earthquake risks.	- Production of circular products for cultivation purposes. - Sustainable solution to support local activities.
23. South AlBtinah (Oman)	DCS5	465,550	- Increasingly compromised water resources. - Increasing rates of salination of groundwater. - Agricultural output is on decline, resulting in many farmers deserting their lands.	- Degradation of soils.	- Tackling the increasing rates of salination impacting the properties and quality of groundwater. - Obtaining limited volumes of pure water that could support high-end vegetable or fruit production. - Improve the use of land. - Making brackish suitable for agriculture and other purposes.
24 and 25. Hulu Langat and Damai Riverview (Malaysia)	Hulu Langat: DCS 6; Damai Riverview: DCS 3 + 4	–	- Abundance of rainwater, but unevenly distributed. - Utilisation of groundwater is relatively low. - Inadequate water resources recharge. - Water scarcity is getting prominent in some decentralised areas. - Water consumption is increasing. - Water pollution due to unsustainable development. - Inconsistent water supply with low-quality water. - Touristic pressure.	- High risk of flooding. - Area covered by forests, which are under protection of Selangor's Eco Park. - Diminishing available clean water due to environmental issues.	- To upgrade water infrastructure in the area. - To provide alternative water sources. - To improve resilience to flooding. - Serving as first example to educate the locals.
26. Gatton campus (Australia)	DCS 1 + 2	2,100	- Region highly dry. - Rainfall is highly variable, with regular prolonged periods of droughts. - The evaporation rate is substantially higher than the annual rainfall (1893 mm vs 669 mm). - WWTP needs to be upgraded. - High dependence on bore water for irrigation. - Decreasing levels of aquifers. - Large volumes of organic waste streams. - Energy crisis (fertilisers prices have increased significantly).	- The area has moderate slope (from 90 to 35 m). - The replication site is prone to flooding.	- To improve waste and energy management. - To bring economic benefits from waste management. - To contribute to the ambition of becoming self-sufficient and carbon neutral. - To reduce the emissions of local industry wastes. - To avoid vamping wastewater to other WWTPs. - To become a leader in sustainable solutions.

(Fig. 3), suggesting that, in general, local regulations would not hinder the implementation of DCS. However, none of the sites showed very high scores, which indicates that the legislative framework at these sites did not prioritise the implementation of these alternative solutions over conventional ones. The only exceptions that achieved medium feasibility scores were: i) Culatra (Portugal), due to the prohibition of producing drinking water from rainwater and building greenhouses in the area; ii) Nattoufa (Israel), basically due to the strong Israeli policy to reinforce centralised systems, not showing ad-hoc instruments for small-scale systems (Abraham et al., 2019); and iii) Mezcala (Mexico), which showed plenty of legislative gaps such as ambiguous and outdated legislation, unclear guidelines for water reuse practices, lack of targets or specific standards related to water management, unclear procedure for environmental impact assessment, and lack of instruments for GPP (Table S7).

Unlike social and legislative assessments, technical feasibility assessment scores were highly variable (Fig. 4). It must be noted that information on the specific amounts of circular products to be produced in each replication site was not provided (confidential data). In DCS-1+2, most of the sites that showed medium or low scores were influenced by the low scoring obtained in compost production. It is important to note that for reclaimed water production, which is the main product of DCS-1+2, high or very high scores were obtained at all sites, but Cabrera and Saint Honorat obtained scores of 15 % and 65 %,

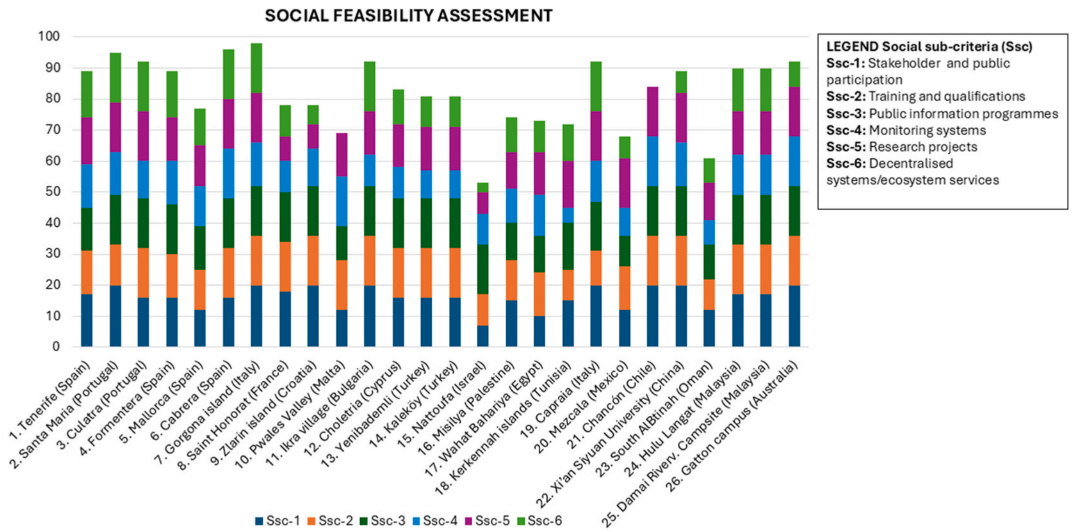

Fig. 2. Social Feasibility Assessment.

Table 2
Relevant elements for legislative analysis of each decentralised solution (DCS).

DCS	SITES	INPUTS	OUTPUTS	COMMENTS
DCS 1 + 2	- Gorgona island (Italy) - Ikra village (Bulgaria) - Saint Honorat (France) - Mallorca and Cabrera (Spain) - Choletria (Cyprus) - Yenibademli (Turkey) - Nattoufa (Israel), - Genin (Palestine) - Wahat Bahariya (Egypt) - Mezcala (Mexico) - Chancón (Chile) - Xi'an Siyuan University (China) - Gatton Campus (Australia)	- Municipal wastewater.	- Reclaimed water for irrigation. - Compost/biosolids (fertilizer/soil amendment). - Biogas/biomethane. - Fruits/crops/bushes.	Regulatory instruments of DCS 1 and 2 were assessed together as these solutions were closely related and normally form a single system (DCS 1 + 2).
DCS 3 and 4	- Zlarin island (Croatia) - Pwales Valley (Malta) - Culatra and Santa Maria (Portugal) - Cabrera, Tenerife (Spain) - Capraia (Italy) - Kerkennah islands (Tunisia) - Damai Riverview Campsite (Malaysia)	- Rainwater. - Runoff/stormwater.	- Water for irrigation. - Aquifer recharge. - Essential oils. - Rainwater for domestic non-potable purposes.	Regulatory instruments of DCS 3 and 4 were assessed together as both are related to rainwater/stormwater collection.
DCS 5	- Pwales Valley (Malta) - Culatra Island (Portugal) - South AlBtinah (Oman)	- Seawater. - Saltwater/brines.	- Water for irrigation. - Tropical fruits. - Salts from brine.	As water for irrigation was contemplated on other DCSs and fruits are generic products, legislation of DCS-5 mainly focused on brines management.
DCS 6	- Formentera (Spain) - Kaleköy (Turkey) - Hulu Langat Home Stay EcoFarm (Malaysia)	- Rainwater. - Domestic water (greywater). - Domestic water (blackwater). - Water vapour.	- Water for irrigation (from rainwater). - Reclaimed water for irrigation (from greywater). - Compost. - Vegetables/fruits. - Drinking water from vapour. - Rainwater for domestic purposes.	DCS-6 combines many of the solutions/technologies of other DCSs (water reuse, composting, rainwater and stormwater collection, etc.).

respectively (Fig. 4a). DCS-3, the simplest solution, obtained very high scores for all replication sites (Fig. 4b). This indicates that the amount of rainfall at the sites, as well as at the selected surface, was appropriate. Regarding DCS-4, Culatra (Portugal) and Tenerife (Spain) obtained high technical feasibility scores, whereas in Cabrera (Spain), the score was medium, and in Damai Riverview (Malaysia), it was low (Fig. 4c). This was related to the reduced volume of the storage tanks, which were designed to limit construction costs. In DCS-5, Culatra showed technical difficulties with all circular products, whereas in the Maltese case, the medium score was due to the low amount of freshwater produced (Fig. 4d). With respect to DCS-6, the medium score of Kaleköy (Turkey) was significantly affected by the low collection of atmospheric vapour (Fig. 4e).

The scores were quite variable in the economic feasibility assessment, with a slight predominance of high economic feasibility at 12 out of 26 sites (Fig. 5). The CAPEX scores of DCS-1+2 were significantly

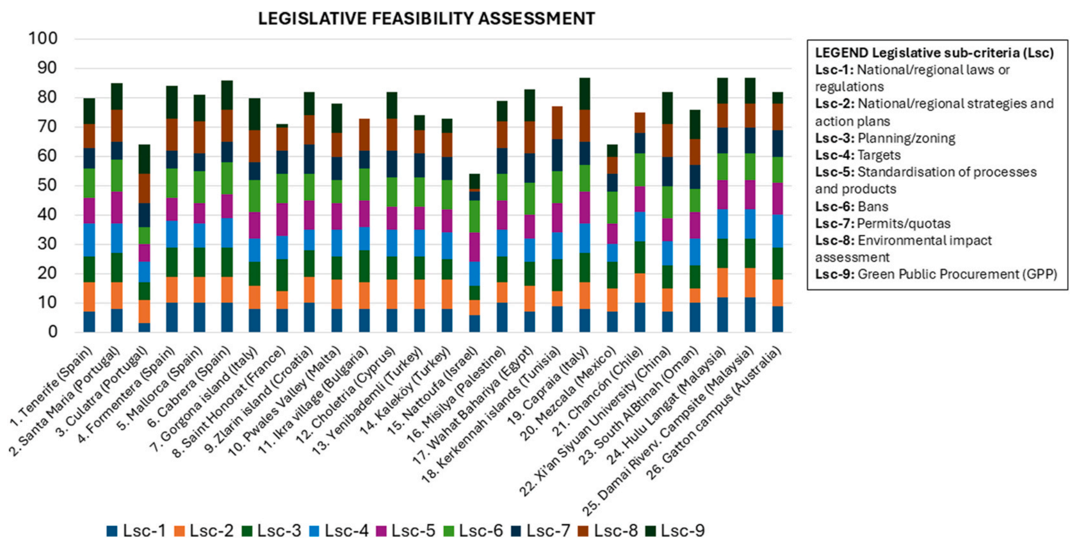

Fig. 3. Legislative Feasibility Assessment.

higher than the others (data not shown, confidential). Conversely, there were nine sites where the economic feasibility was low or very low, which means that some hurdles related to economic issues were detected at those sites. In Culatra (Portugal) and Pwalles Valley (Malta), economic feasibility was calculated without considering the possible financial instruments that could be potentially applied to the two sites (due to lack of information from the local sites). This indicates that their scores may be higher. In Yenibademli (Turkey), low scores were influenced by the low income from wastewater treatment taxes (0.11 €/m^3).

In summary, the results of the overall feasibility assessment showed that most EU replication sites obtained high scores, except for the Maltese, Saint Honorat, and Culatra sites, which had medium scores (Fig. 6). These results are significantly influenced by the high social and political acceptance of DCS at most sites. These high scores compensated for some medium scores obtained in the technical and/or economic assessments of some sites. However, for the non-EU sites, medium overall assessments accounted for seven of the 13 sites (Fig. 6). All sites with medium scores (European and non-European) were influenced by low economic feasibility, except for DCS-5 in Culatra, which was negatively influenced by low technical assessment scores (Fig. 6).

4. Discussion

In addition to assessing the potential implementation of DCS in the selected replication sites, the results obtained from the QFAM provided useful insights to evaluate the current status of sites in terms of the social, legislative, technical, and economic factors analysed (at the local, regional, national, and/or continental levels). This general evaluation highlighted the potential benefits of DCS on the sites and detected possible gaps and barriers to be overcome.

4.1. Social feasibility assessment

In general, local stakeholders showed high interest in DCS, which aligns with the high social feasibility scores generally obtained at the sites (Fig. 2). However, social feasibility scores were influenced by the fact that they considered not only the current situation, but also the potential social instruments that are planned to be implemented on the sites. At most sites, local stakeholders considered the proposed solutions as the first case studies to initiate the transition to more sustainable water management technologies and techniques in their regions. At some sites, such as Mezcala (Mexico), Chancón (Chile), and Hulu Langat (Malaysia), DCS was also considered as a possible solution to cover basic needs that are currently lacking, that is, efficient wastewater sanitation. This is relevant because circularity-based policies are often hampered by a lack of trust between decision makers and local stakeholders (Cipolletta et al., 2021; Nika et al., 2020). Previous studies have also shown that local communities are open to using alternative water sources for domestic applications, but the acceptance of alternative water technology is influenced by risk and threat perceptions, water culture, and motivational drivers (Mankad and Tapsuwan, 2011). However, at sites such as Nattoufa (Israel) and Mallorca (Spain), the interest of stakeholders was less significant. This was probably related to the fact that they already have other sanitation and pollution-control systems based on centralised solutions (Pons and Rullan, 2014); therefore, the DCS proposed in this study were not considered basic (and urgent) needs. Some limited social scores were also related to existing challenges detected at some sites, such as cultural resistance, lack of understanding of decentralised systems, and resource constraints (Cipolletta et al., 2021). To address these challenges, it is crucial to involve the community in the project design and implementation stages and collaborate with local organisations and specialised stakeholders, as they could help build support and promote local engagement. Public involvement can provide relevant inputs for decision-making processes, build consent for solutions, and help identify problems associated with alternatives (Domènech et al., 2013; Mankad and Tapsuwan, 2011). However, maintaining good collaboration between groups of stakeholders is difficult. Misunderstandings between the different levels of water governance (national, regional, and local) were common in all countries assessed. This is remarkable in the case of Spain, where the islands present an extra administrative government in comparison to regions from the mainland. It was also found that non-specialised stakeholders commonly feel reluctant to participate actively and express their ideas and worries about local situations, which hinders their involvement in the decision-making process. Thus, it is important to identify actors who can facilitate communication between specialised and non-specialised stakeholders. Researchers and academics are good options because they have experience with training and communication. They are normally at the front line of the transition to sustainable water management. In this respect, the involvement of universities and academia in evaluating the implementation of DCS was high at most sites (Table S6). Many of the sites relied on manual operations, preferably carried out by local workers who required a training period to develop their work. Hence, there is high potential for implementing automatic monitoring systems. Negotiations with the owners of viable land for installing the DCS were also detected as a significant challenge.

Fig. 4. Technical Feasibility Assessment.

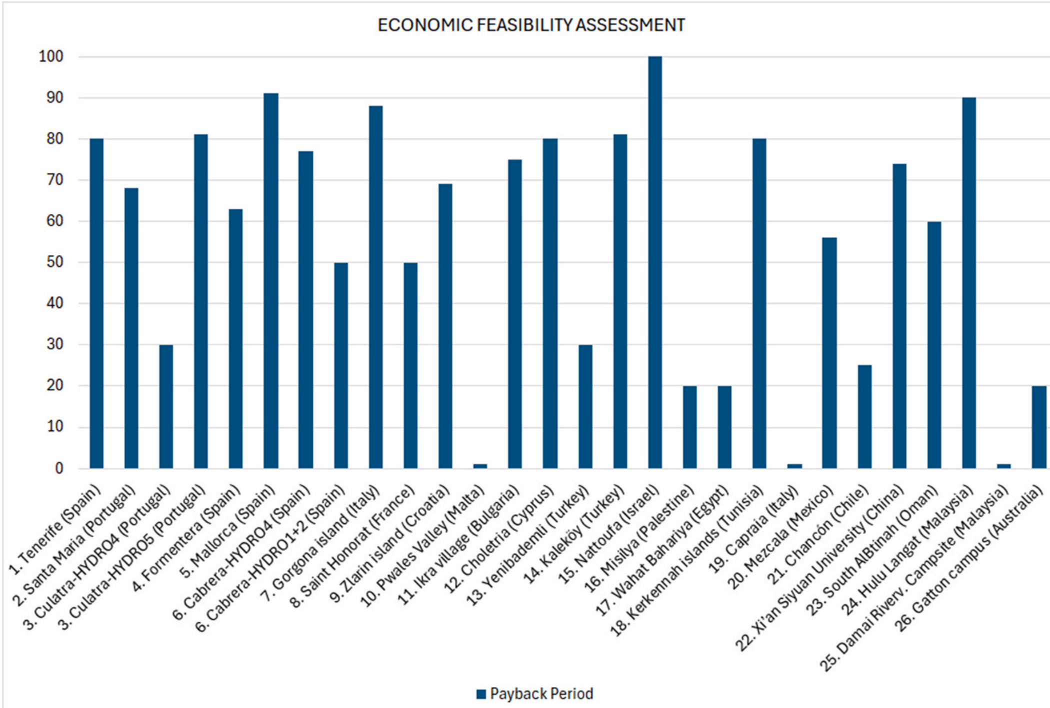

Fig. 5. Economic Feasibility Assessment.

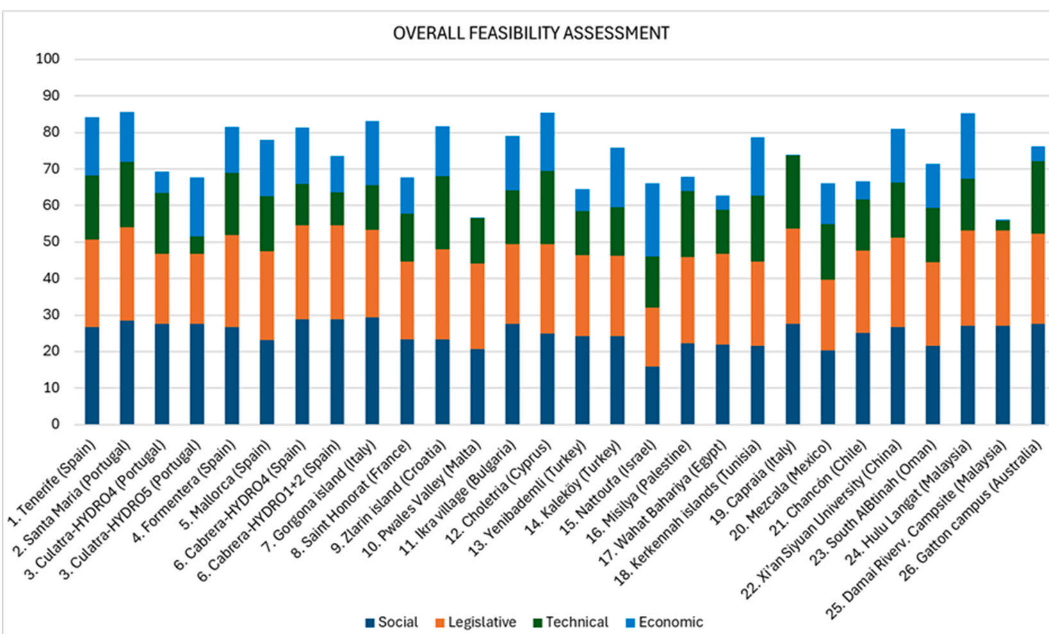

Fig. 6. Overall Feasibility Assessment.

4.2. Legislative feasibility assessment

From a legislative perspective, the replication sites evaluated in this study can be merged into two main groups: i) EU replication sites, in which legislation commonly presents standard regulations at the continental level, and ii) non-European sites, whose regulations differ significantly at the national level, as their current legal situation is quite different and their policies generally follow different objectives. In general terms, the legislative approach in regions belonging to Turkey, China, Australia, and Israel was more similar to that in Europe, where water management regulations and plans mainly aim to improve sustainability. At other sites, such as Mezcala (Mexico), Chancón (Chile), and Hulu Langat (Malaysia), water management is considered an urgent issue because they do not have appropriate infrastructure to ensure environmental and health security. For this reason, water regulations in these countries focused on achieving appropriate levels of water sanitation, rather than implementing sustainable practices. In addition, in a generic way, it seemed that possible legislative barriers were less severe in non-European sites than in European sites, which were normally more restrictive in the use of circular by-products owing to health risk concerns (Radini et al., 2023). However, more non-European sites belonging to regions less covered in this study (such as Central America and Central/Southern Africa) should be conducted to confirm this statement.

It must be also noted that legislation related to closing water loops is generally complex and fragmented, presenting several directives, national and local regulations that must be consulted prior to assess the implementation of alternative solutions (Cipolletta et al., 2021). Moreover, the procedures and administrative duties for obtaining permission to build the DCS, although standard, generally lack simplified authorisation procedures for decentralised systems, as well as the lack of benefits in terms of green public procurement, which was found to be scarcely implemented in non-European sites (with some exceptions such as China and Malaysia, observed in Table S7). Simplifying procedures and permits is important, for instance, to ensure that the implemented DCS will not cause any significant damage to users and the environment. It is also necessary to improve communication between different levels of governance (local, regional, and national) to align water policies and make them more sustainable (Trapp et al., 2017).

Legal uncertainty regarding some of the circular practices and products developed in the DCS was also detected at most sites. Because these circular approaches are relatively novel, they are often not specified in the regulations, leading to legislative gaps that can hinder the legal implementation of alternative solutions. The lack of specific legislation for decentralised systems is also common at the replicated sites. Especially remarkable were the Israeli and Spanish cases, which have created policies that rely heavily on centralised water management systems, as they consider centralisation as the most efficient approach in most cases. In Europe, the level of treatment and monitoring requirements for reusing wastewater is increasing, with the goal of ensuring the safety of end-users and the environment (Radini et al., 2023). It is challenging for small systems to cope with the same requirements as centralised systems, particularly when a new WWTD (European Parliament, 2024) is applied. This can be counterproductive globally. Considering that the future WWTD only forces the installation of sanitation systems in populations with over 1,000 inhabitants, many end-users and water authorities could feel discouraged in implementing decentralised systems to treat and recover wastewater in rural areas. However, in many replication sites (such as Italians, Mexican, Malaysian, Chilean, Bulgarian, etc.), the current situation is worse in terms of water scarcity and environmental pollution than expected in water reuse scenarios. This finding is supported by several studies (Foglia et al., 2021; Jiménez-Benítez et al., 2020). Hence, the potential discouragement caused by excessive requirements seems to be worse than simplifying the standards of treatment for decentralised systems in comparison with centralised systems. In the EU context, an Innovation Deal approach is recommended to develop possible solutions to implement policies that differentiate the legal requirements to be accomplished in centralised or decentralised systems (Cipolletta et al., 2021).

Other legislative issues were detected in the replication sites:

The use of reclaimed water for irrigation is generally well defined, except in developing areas such as Mezcala and Chancón. Detailed information was provided on the legal limits for water quality criteria, frequency of monitoring, and, in the case of European sites, risk management practices (Radini et al., 2023).

Fertigation, that is, the simultaneous application of reclaimed water and nutrients to croplands (Foglia et al., 2023), is not generally considered in the water reuse regulations of the sites, which is a common practice in many countries, especially in developing economies (Adegoke et al., 2018; Chojnacka et al., 2020).

The use of rainwater and/or stormwater for irrigation is generally not defined, except at some sites such as El-Wahat Bahariya (Egypt), where it is only partially defined. This is related to the fact that both rainwater and stormwater are generally considered within urban wastewater streams as they are usually collected in the same sanitation system. This creates a gap, assuming that legislation on wastewater reuse would be applicable to DCS-3 and 4, which is unclear. As rainwater is expected to present much lower amounts of pollutants than wastewater and stormwater, applying the same quality and control restrictions to all of these waters would hinder the operation and maintenance of DCS, making them less technically and economically feasible (Vasilakos et al., 2023). A similar issue was detected for greywater and blackwater, which could have hindered greywater recovery in DCS-6 (Section S4.7).

- Sewage sludge (preferably stabilised by composting) can be applied to soils in some cases, but this practice tends to disappear in Europe due to the last regulation on fertilisers, i.e., the “Fertiliser Di’rective” 2019/1009. This regulation does not include sewage sludge as a component of commercial compost, because of its possible risks to human health. This is a clear barrier for DCS-1, although this compost can be used in certain on-site applications without being commercialised (Section S4.2).
- Partial information exists regarding the quality and origin of biogas/biomethane. However, legal instruments at the sites evaluated focused on large industrial plants, commonly obviating decentralised systems. The potential commercialisation of the biomethane produced in DCA-1 is also unclear because of its low economic profitability (mainly owing to low gas production) and legal requirements in terms of gas quality and safety measures to be addressed (Liu et al., 2014).

Drinking water production from rainwater is generally unclear and controversial and is completely forbidden in Portugal. At other sites, specific information on the recovery of drinking water from vapour is generally lacking. Thus, it is assumed that the drinking water produced by DCS-4 and DCS-6 should meet the same requirements as those of industrial systems to ensure consumer safety. This can be a significant barrier to recovering potable water in the DCS, as the new Directive on Drinking water is expected to increase the focus on monitoring emerging contaminants (European Parliament 2022).

- Irrigation of edible crops with wastewater and stormwater is sometimes controversial for food safety reasons.

Considering the above, to boost the implementation of decentralised systems to close water loops, the following legal procedures should be implemented:

- Consider the specificities and possibilities of decentralised systems, differentiates their operation and monitoring from centralised systems, and their requirements for design, construction, and maintenance.
- Contemplate, regulate and standardise innovative practices that have been proven to be efficient, sustainable, and safe for certain applications, such as fertigation, reuse of rainwater, stormwater, greywater (and others), brine recovery, and biomethane production from wastewater.

Define different alternative water streams (rainwater, stormwater, saltwater, greywater, and blackwater) and specify their possible reuse and quality requirements. In this case, it would be advisable to promote the construction of infrastructure and facilities that can separate these streams as long as they are feasible and sustainable.

- Promote the development of green policies to support sustainable technologies, such as GPP initiatives (Lucarelli et al., 2020; TEG, 2020).

Mitigate administrative procedures for the application of decentralised systems for resource recovery.

4.3. Technical feasibility assessment

Regarding the technical feasibility, minor issues were detected for some of the solutions. In the case of DCS-1+2, the urban wastewater at the sites generally appeared to be low organically loaded. Consequently, their capacity to produce sludge for composting is limited. This also affects biogas production, albeit to a lesser degree. An option to increase the organic load of DCS could be to add the organic fraction of municipal solid waste (OFMSW) produced by locals (Moñino et al., 2016). This could also facilitate waste management at the site. In any case, this option would make sense only if the compost produced in the DCS obtained permission for use, which was unclear after the Fertiliser Directive 2019/1009 was applied at the national level (Section 4.2).

Regarding DCS-6, the vapour-collecting system should be optimised to improve efficiency and increase the technical assessment. However, this would increase the energy consumption. Considering that the legislation regarding alternative sources of drinking water is highly restrictive (as explained in Section 4.2), the implementation of vapour-collecting systems following the principles of DCS-6 is not technically feasible. A more realistic approach is to collect alternative water sources (reclaimed water, rainwater, saltwater, and stormwater) for non-drinking purposes (both domestic and non-domestic). This would (indirectly) increase the water sources available for drinking at the replication sites by reducing the consumption of surface water and groundwater for irrigation and domestic use. No major technical issues were identified during the DCS.

4.4. Economic feasibility assessment

In general, the replicated DCS were profitable, considering that the revenues obtained from their circular products were normally higher than the production/treatment costs. Consequently, their economic feasibility is highly dependent on their initial investment in implementing the solutions. This was more remarkable for DCS-1+2, in which the CAPEX was significantly higher than that of the other solutions (data not shown, confidential). This is a relevant factor that could discourage local administrations from investing in this technology, especially in regions that are more economically limited or have priorities other than wastewater treatment and sanitation. Therefore, potential financial instruments (such as tariffs, subsidies, and transfers) that could be applied at these sites were also considered. They can cover (partially or totally) the initial investment, thereby reducing their ROI and obtaining high economic feasibility scores. These sites were divided into two main categories: i) sites with a specific water financing structure where water tariffs are applied to end users to cover the CAPEX and OPEX, either from direct users or distributed among the population (Cipolletta et al., 2021; The European House, 2022); and ii) sites with financing strategies derived from subsidies from local, regional, or national public bodies or water service operators. These financial instruments provide universal and equitable access to drinking water and sanitation. Transfers (from foreign countries, NGOs, or EU funds) can also be used to cover investment costs for building or revamping water infrastructure, targeting vulnerable and less developed areas (Cipolletta et al., 2021). In addition, the DCS can obtain funding from economic activities, such as agriculture and tourism, which could be coupled with them. It must be noted that some of the sites presented many financial instruments to implement DCS, thereby obtaining high economic feasibility scores. The case of Nattoufa was especially remarkable, as it obtained the maximum score because in Israel, water tariffs should enable the full-cost recovery of water systems, including the costs of land acquisition, water conveyance, piping systems, and wastewater treatment. In addition, reclaimed water can be paid up to 0.4 €/m^3. However, on sites such as Mezcala (medium score), the only financial instrument is a loan. Conversely, sites that did not find external financial sources (such as the Pwales Valley and Damai Riverview Campsite) displayed low scores and were economically unfeasible (Fig. 5).

An exception is Capraia (Italy). At this site, DCS-3 was not economically feasible, as no income was obtained from the rainwater collected; therefore, they obtained a minimum economic feasibility score. However, the local authority considers DCS-3 as a water service to be provided to a decentralised region, substituting the current approach of providing it with water from the mainland. This implies much higher costs than DCS-3, as well as higher environmental and social impacts. This issue has not been considered in the current version of the methodology. Future implementation of the methodology could include a comparison between the scenario of replicating the DCS and the current situation at the sites, although this could increase the complexity of the data-collection process.

4.5. Overall feasibility assessment

According to the high or medium overall feasibility assessment scores obtained (Fig. 6), the DCS was generally well-received by local stakeholders, who were highly interested in the solutions in most cases. Therefore, the replication of DCS would be potentially successful at the 26 sites evaluated. This suggests that these DCS can be adapted to diverse regions worldwide. However, these results presented some subjectivity as the scores were applied according to the evaluator's perception. This is common in MCDA methodologies (Ruangpan et al., 2021; Triantaphyllou, 2000). Therefore, it is assumed that the level of detail of the information provided by the scores is also limited. Despite this, the information obtained can be useful for preliminarily evaluating whether DCS can be successfully replicated at the site or if there are potential barriers to their implementation. If the DCS is implemented at the site, a more detailed site-specific analysis is needed.

Despite the high scores, several issues were detected at most sites, which could complicate the implementation of DCS from a practical perspective. Generally, there is a lack of understanding of the specificities of decentralised systems by local authorities and administrations who tend to prefer centralised water management systems and policies. Consequently, there are few legal instruments specific to decentralised systems. This, together with other issues such as the lack of simplified authorisation procedures for decentralised systems or not contemplating some circular practices and/or products developed in the DCS, can reduce the competitiveness of the DCS in comparison to conventional centralised systems. It must also be noted that it is important to assess (numerically) the non-economic benefits provided by the DCS for the economic feasibility of the solutions. This provides a more realistic comparison between the non-action scenario and scenarios in which DCS are implemented.

5. Conclusions

Six DCS solutions for recovering alternative water sources and circular products were replicated at 26 international decentralised water-scarce sites. A feasibility assessment methodology based on MCDA was used to evaluate replicability, providing quantitative scores for relevant social, legislative, technical, and economic factors. From the overall results, the DCS were highly accepted by the locals, as all replication sites obtained high or medium overall feasibility assessments. European sites presented some similarities, especially regarding common legal frameworks. In the case of the non-European sites, the scores varied owing to their significantly different local specificities and needs. High overall scores were primarily influenced by good social and legislative assessment scores. However, some issues were identified. Local authorities and administrations tend to centralise their water infrastructure, often obviating the specificities of decentralised areas. Consequently, many legal gaps were found regarding the circular practices and products produced by the DCS, which were generally not specified in local legislation. Other potential barriers were related to the complexity of water-related legislation and authorisation procedures to build the DCS and the strict requirements for implementing the solutions, especially in European sites, as well as cultural resistance to change and misunderstandings between different levels of water governance. However, technical and economic assessments sometimes showed medium or low scores and were highly influenced by the presence or absence of financial pathways to invest in the DCS. Considering that the main goals of DCS are related to non-economic factors, it is essential to improve the feasibility assessment to quantify these non-economic benefits to provide a more realistic comparison between DCS replication scenarios and current scenarios at the sites.

CRediT authorship contribution statement

J. González-Camejo: Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **L. De Simoni:** Writing – review & editing, Project administration, Investigation. **N. Kamergi:** Writing – original draft, Formal analysis, Data curation. **E. Mino:** Writing – original draft, Formal analysis, Data curation. **A.L. Eusebi:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **F. Fatone:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition.

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.

Acknowledgments

The authors acknowledge the EU's Horizon 2020 research and innovation programme for funding "HYDROUSA" project under grant agreement 776643. Authors would also like to acknowledge all the people who contributed to obtain information from the replication sites.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125481.

Data availability

The authors do not have permission to share data.

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