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DOI
10.1016/j.jclepro.2025.145874

Publication date
2025

Document Version
Final published version

Published in
Journal of Cleaner Production

Journal of Cleaner Production 517 (2025) 145874

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Developing a framework to assess water smartness and sustainability of circular economy solutions in the water sector

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A R T I C L E I N F O

Keywords:
Sustainable development
Circular economy
Integrated water management
Water smartness
Resource recovery
Stakeholders' involvement

A B S T R A C T

The transition to a circular economy in the water sector is challenged by the lack of comprehensive tools to assess and compare the performance of innovative solutions across multiple sustainability dimensions. This study aims to develop a structured framework of indicators to support such assessments and guide the sector toward achieving the United Nations Sustainable Development Goals (SDGs). The framework was co-developed with stakeholders and encompasses technical, social, environmental, economic, and governance dimensions. It is organized into four hierarchical layers: dimensions, objectives, criteria, and indicators. Objectives were designed to be broadly applicable, while criteria and indicators were formulated to assess alignment with these objectives and capture the multifaceted nature of "water smartness." The framework was tested and validated through workshops and structured engagement activities across six demonstration cases. Results from exploratory data analysis confirmed the framework's relevance for decision-making, highlighting its capacity to compare alternatives under diverse scenarios and its alignment with the SDGs. Additionally, the testing process pointed out the differentiated responsibilities of involved stakeholders, offering practical insights for advancing full-scale implementation of circular economy models in the water sector.

1. Introduction

Anthropogenic activities, such as agricultural intensification, industrial pollution, climate change and urban development, have put pressure on aquatic ecosystems worldwide (Bosco et al., 2023; Hernes et al., 2020). At the same time, degrading soil quality and increased hydrological stress in many of the world's important food producing areas are caused by expansion of urban areas and poor farming practices. These challenges are increasingly recognised by the water sector, including both water supply and wastewater management (European Environment Agency, 2024).

Over the past two centuries, linear economic models, characterized by the "Take-Make-Waste" approach, have driven remarkable societal progress but have also resulted in significant environmental and social drawbacks (Seiffert and Loch, 2005). In recent years, attention has increasingly turned toward more sustainable models that prioritize a balance among economic growth, social equity, and environmental preservation for both present and future generations (Jum'a et al., 2022). The concept of Circular Economy (CE) is a component of this transition, aiming at transforming waste into valuable resources and at achieving long-lasting service and products (Geissdoerfer et al., 2017). This approach has gained global traction in response to dwindling natural resources and rising consumption demands (Jackson, 2009).

In the water sector, the development of effective CE models for resource recovery and wastewater reuse will be crucial to ensuring the sustainable management of water in the future (European Commission, 2024). The concept of water smartness (Water Europe, 2023) links the water sector with the concepts of sustainability and more specifically of circular economy. According to Water Europe, the features connected with a water-smart society relate to the capacities of properly addressing the value of and in water, water management, water scarcity, water pollution, resource efficiency, and resilience. Moreover, for future water smart society, enhanced stakeholder engagement plays a key role in decision-making processes, stimulating active collaboration, public-private partnerships and increased industrial symbiosis (Yadav et al., 2021). These dimensions of water smartness contribute directly to

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https://doi.org/10.1016/j.jclepro.2025.145874
Received 18 December 2024; Received in revised form 28 May 2025; Accepted 30 May 2025
Available online 2 June 2025

sustainability by promoting efficient resource use, pollution reduction, and climate resilience, while the emphasis on resource recovery, industrial symbiosis, and stakeholder collaboration aligns with the core principles of the circular economy, namely, retaining value within systems, minimizing waste, and fostering closed-loop processes (Agostinho et al., 2024). The concept of water smartness remains inadequately defined within the existing literature, leading to ambiguity regarding the quantification of its relationship with circular economy (CE) principles through the application of various technologies, both established and emerging (Smol et al., 2020). This lack of clarity poses a risk that the technologies implemented may not always be optimal, scalable, or widely adopted (Fersi et al., 2015; Medina-Martos et al., 2020).

Recent efforts have been made to define water smartness and establish its connection to CE. One such study derived its definition from a combination of stakeholder interviews and a comprehensive literature review, proposing several economic, regulatory, and informational measures to advance water smart CE solutions (Salminen et al., 2022). Another investigation cantered on business models associated with smart CE, particularly highlighting the digital dimensions and the potential for collaboration among companies in business-to-business (B2B) contexts (Alcayaga and Hansen, 2025). Another study focused more on the role that CE will have for more sustainable development and presented various archetypes of business models, drivers, and barriers (Awan and Sroufe, 2022). Additionally, specific opportunities and pertinent CE business models relevant to the water sector have been identified (Smol et al., 2023). A framework has also been created to assess the impacts of implementing CE solutions within the water sector (Smol, 2023); however, this framework does not adequately address the required industrial symbiosis nor offer guidance on selecting appropriate solutions. Another recently proposed framework examined how to assess and compare the sustainability of waterworks operations (Sala-Garrido et al., 2023). The focus on the operation of waterworks makes the framework less transferable to other parts of the water sector and for selecting solutions, but it shows interesting results from varying weightings of values.

Conversely, it can be posited that numerous process technologies essential for a water-smart and CE within the water sector are relatively advanced. However, legislative, social, organizational, and economic challenges often impede the adoption of such practices in this field (Mannina et al., 2021). Additionally, the diversity of stakeholders involved in circular economies in the water industry is noteworthy, encompassing water utilities, regulatory authorities, technology providers, farmers, and citizens, among others (Chrispim et al., 2020). Therefore, fostering awareness and building knowledge is vital to enhance decision-making processes (Damman et al., 2019). Sustainability encompasses multiple dimensions, including environmental, societal, and economic aspects, leading to the development of various assessment frameworks. These frameworks aim to systematically integrate a diverse range of indicators (Preisner et al., 2022). The significance of such integrated, multidimensional assessment frameworks is particularly pronounced in the water sector, where challenges are complex and interconnected. There is a pressing need to equip decision-makers with the tools to assess, rank, and select appropriate solutions (Damman et al., 2023; Helness et al., 2017; Shanmugam et al., 2022; Smol, 2023). However, literature currently lacks frameworks that effectively combine sustainability with water smartness and circular economy principles. To address this shortcoming, the present study introduces a comprehensive framework specifically designed to integrate these aspects and support practical assessment and implementation within the water sector.

The objective of this study has been to develop a framework that will meet the needs of assessing the water smartness and sustainability deriving from industrial symbiosis of solutions in the water sector. This development was centred around six real case studies as part of the EU project WIDER UPTAKE,[1] taking into consideration different processes and contextual challenges towards the practical implementation of industrial symbiosis at full scale. More specifically, this paper aims at:

1. Demonstrating how the developed framework connects to the SDGs.
2. Validating the framework relevance based on a structured feedback analysis.
3. Testing the framework usability in six real case studies.

2. Methodology and methods

2.1. *Definition of symbiotic CE solutions*

For a given technical solution, the integration of stakeholders, recovery processes, recovered resources, business models, and final products and applications helps define the boundaries of a unique ecosystem. This system, referred to as a Symbiotic Circular Economy Solution (SCES), establishes complex interactions with the environment, economic actors, society, and regulatory authorities. In contrast to traditional water services, such as conventional wastewater treatment plants (WWTPs) that primarily focus on pollution removal, SCESs are designed to recover valuable resources (e.g., water, material, energy, nutrients), develop marketable products, and generate systemic value for multiple stakeholders. This broader functionality introduces new performance dimensions that require distinct objectives, criteria, and indicators to evaluate their water-smartness and sustainability. Unlike classical circular economy approaches, which often focus on optimizing material and resource flows within individual systems or organizations, the SCES concept emphasizes the systemic integration of diverse actors across sectors. It promotes collaboration and mutual value creation by enabling synergies between water utilities, industries, policy-makers, and communities. In this way, SCESs aim to deliver context-sensitive, adaptive, and scalable circular solutions that respond to local environmental and socio-economic conditions, ultimately fostering more resilient and inclusive circular transitions. The hereby proposed definition of the SCES, as depicted in Fig. 1, represents the foundation for the creation of the proposed assessment framework to address sustainability and CE models in the water sector. The figure also indicates the interactions between the SCES and society and nature with respect to inputs and positive and negative impacts. Further, return of impact and waste or resource flows in society and nature are indicated to highlight circularity.

The four pillars of the SCES are (i) partners and stakeholders that collaborate to implement the solution, (ii) recovery processes and recovered resources, (iii) business models that valuate the transformation of recovered resources to products, and (iv) applications and final products. The selection of these four pillars reflects the underlying hypothesis of WIDER UPTAKE that more than technical solutions are needed for realization of circular economy value chains, i.e., symbiotic collaboration between different partners of the solution and viable business models that place products derived from the recovered solutions into circular economy value chains. The phrasing of the objectives, criteria, and indicators included in the framework were based on the proposed SCES structure, considering inputs and outputs related to nature and society with their several sub-interactions that need to be understood and monitored to enable the SCES' prosperity over time. The level of water smartness of a given SCES is captured through the indicators' values of the framework, possibly for a variety of alternatives and scenarios, which are based on boundaries set by the definition of the SCES. Alternatives represent available options through choices made by the partners involved in the SCES, while scenarios are defined as possible futures arising from changes outside the control of the partners.

[1] https://wider-uptake.eu/.

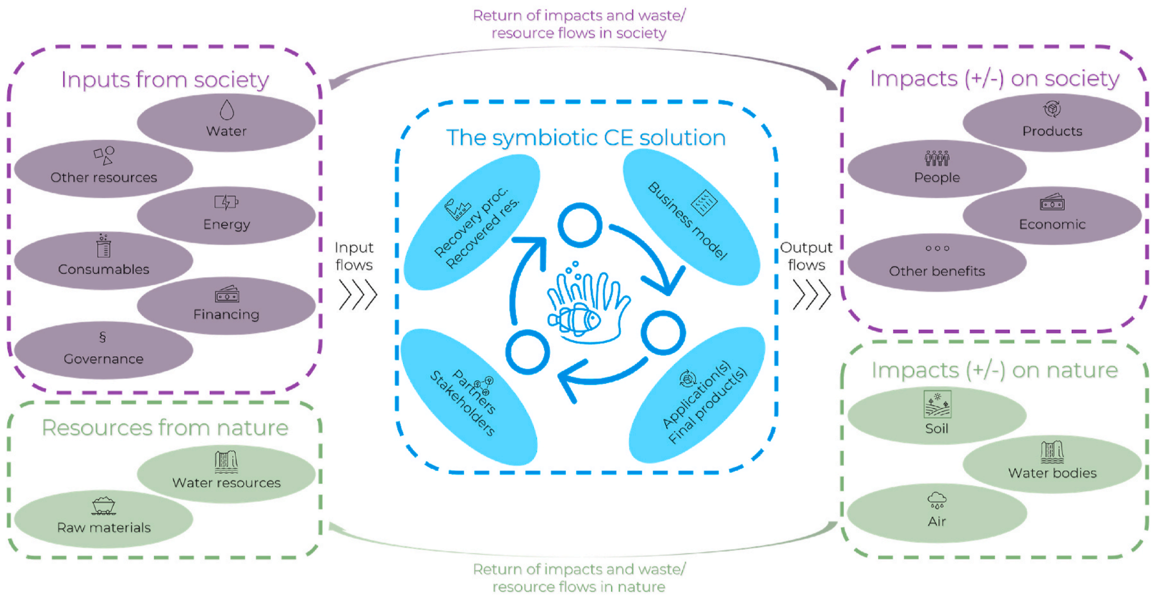


Fig. 1. Illustration of properties of a SCES and the inputs and impacts related to society and nature.

Alternatives typically refer to different technical, organizational, or managerial configurations of a solution that stakeholders within the SCES can select or influence. In contrast, scenarios are broader contextual developments, such as regulatory changes, demographic shifts, or climate impacts, that cannot be directly controlled by the involved actors. Scenarios are generally co-developed with stakeholders using foresight or participatory methods, and they are used to test the robustness and adaptability of alternatives under different plausible future conditions. The evaluation of scenarios and alternatives is carried out by the interested stakeholders using the framework's indicators to assess the performance of the SCES across multiple dimensions of water smartness and sustainability.

2.2. The structure of the framework

The choice of the sustainability dimensions in the proposed framework is based mainly on the approach adopted in the project TRUST (Transitions to the urban water services of tomorrow)[2] and further developed by Helness et al. (2017). In TRUST, the category of infrastructural assets and the category of governance were added as supporting dimensions to the traditional dimensions of society, environment, and economy for sustainability assessment of urban water cycle services. In WIDER UPTAKE, a dimension directly associated to assets seemed to be on a different abstraction level than governance and the other traditional dimensions. Therefore, the WIDER UPTAKE framework mutated the assets dimension from TRUST into the technical performance dimension, as similarly done in the frameworks developed within the projects DRENSTEIN and EviBAN.[3] Overall, the developed framework consists in five dimensions, namely social, environmental, economic, governance and technical performance dimensions. Moreover, the framework was designed to be structured in multiple levels, from the higher level of the five mentioned dimensions to the lower more detailed level of indicators. Specifically, for each dimension, objectives should be defined for which a given SCES is supposed to target to achieve desirable levels of water-smartness and sustainability. Moreover, criteria should be defined to describe how compliance with each objective could be measured. Finally, a set of indicators should be defined to allow a SMART (Specific, Measurable, Achievable, Realistic and Time-bound) quantification of the solution status under the given criterion (Bjerke and Renger, 2017).

The adopted structure in four layers of proposed framework is reflected in the adopted coding of the social (S), environmental (En), economic (Ec), governance (G) and technical performance (TP) dimensions, objectives, criteria and indicators (as shown in Table A1 and Fig. A1, in the Supplementary Material). The framework is not limited to assessing the current demonstration cases but is designed as a generalizable tool for future applications. It provides structured guidance for evaluating new or existing SCES across diverse contexts and scenarios. The steps used to test the framework in WIDER UPTAKE are presented later in the manuscript. The core content of these steps, such as defining scenarios, selecting and weighting indicators, collecting data, and setting input values, are key to conducting a robust sustainability assessment based on the framework. On the other hand, validation activities carried out during the project, such as analytical procedures or participatory workshops aligning the framework with the Sustainable Development Goals (SDGs), were conducted to strengthen and contextualize the methodology, and are not required for general use of the framework.

2.3. Selection of symbiotic CE solutions

To adhere to current challenges in the water sector, six demonstration cases located in five different countries were involved for co-developing and testing the framework. The six case studies were selected based on two main criteria: (i) the representation of diverse climatic and socio-economic contexts, spanning a north-south axis from Norway to Ghana and including various European regions (north, east, and south), and (ii) the inclusion of a broad spectrum of circular economy solutions within the water sector. These include applications in water reuse, nutrient recovery, energy recovery, and materials recovery, ensuring that the framework could be tested across multiple technological domains and governance environments. The descriptions of the demonstration cases are reported in Table 1.

The Sicilian case is fed by municipal wastewater produced by 19,000 p.e. (population equivalent) from which 25 m^3/h are harvested for agriculture purposes. Nitrogen (N) and phosphorous (P) are recovered by using innovative filters filled with special adsorbents such as biochar and zeolite. Nutrient-enriched biochar and zeolite from wastewater

[2] https://trust-project.eu/.

[3] https://www.sintef.no/projectweb/eviban/.

Table 1
The six involved demonstration cases for co-developing the proposed framework.

No.	Description	Place
1	Reuse of wastewater for irrigation and production of slow-release fertilizers in agricultural industry	Sicily, Italy
2	Reuse of wastewater for urban agriculture and production of biochar from wastewater sludge for fuel	Accra, Ghana
3	Fertilizer and soil improver through the resource recovery of waste and wastewater	Hamar, Norway
4	Improved biogas production for the gas grid and fertilizer and soil improver by waste and wastewater resource recovery	Stavanger, Norway
5	Reuse of wastewater for greening the urban areas and cleaning streets	Prague, Czech Republic
6	Production of new bio-composite material and prototype products from resources recovered from wastewater management, drinking water treatment and surface water (canals) management	Amsterdam, Netherlands

treatment can be added directly to agricultural soils as slow-release fertilizers. The Accra case is based on the municipal wastewater of 90,000 p.e. from which 20–30 m^3/h are produced for irrigation and biochar is produced with a capacity of 500–1000 kg/d, to replace the wood fuel sources at around 50 companies. The Hamar case is mostly focused on fertilizers and soil improvers. Specifically, struvite is precipitated through the EBPR (enhanced biological phosphorus removal) which is performed with continuous MBBR (moving bed biofilm reactor) in a WWTP serving 120,000 p.e., consisting of both municipal and industrial wastewater. The production of struvite is around 140–240 ton/a, corresponding to 18–30 tons P/a. The Stavanger case targets the production of both organic fertilizers and increased biogas production, starting from municipal wastewater and treated sludge of 300,000 p.e. The production accounts for 30 tons/d of dry solids, 4000 ton/a of organic fertilizer, and 5000 m^3/d of biogas. The Czech case focuses on the safe use of treated effluent for irrigation purposes in grey-green solutions for urban development. Specifically, the considered municipal wastewater treatment plant serves 800,000 p.e. and the hydraulic capacity of tertiary treatment equals 4.1 m^3/s, from which 2 m^3/d is used for water reuse in a pilot. Finally, the Dutch case consists in utilizing residues from water and wastewater treatment plants (1–4 ton/a of calcite), 0.5 ton/a of cellulose fibers, and 2–7 ton/a of reed clippings for producing 1–10 ton/a of biocomposite material, suitable for different applications in the sector of constructions.

Overall, the variety of recovery processes, final applications, the scales as well as the social context of the selected cases allow to explore from different angles the barriers for implementing at full scale circular economy models in the analysed sector.

2.4. Implemented process to elaborate the content of the framework

2.4.1. Basis for first version of the framework

For the initial version of the framework, objectives, that a water smart solution should contribute to achieving, and criteria, to assess compliance with these objectives, were developed to cover the properties of water smartness identified by the analysis of the Water Europe vision, i.e., value of and in water, water management, water scarcity, water pollution, resource efficiency, and resilience. Further, inclusive multi-stakeholder governance is highlighted in Water Europe's vision. The development and selection of the objectives, criteria, and indicators for the first version of the framework was based on a literature search with an established methodology called CIMO approach (Petticrew and Roberts, 2006), referring to titles, keywords and abstracts. CIMO structures the literature search based on four categories: a. Context (where), b. Intervention (what), c. Mechanism (how), and d. Outcome (result). The search terms in each category are linked together across categories with the Boolean operator AND. The search terms were inserted as follow:

- Context as "'Water smartness' of water management/solutions/practices in wastewater reuse and resource recovery",
- Intervention as "scoping and use of data/information to explain/quantify water smartness",
- Mechanism as "analysis/measurement/calculation/assessment of aspects/factors contributing to water smartness",
- Outcomes as "criteria, indicators, models or index of water smartness".

The literature search was carried out for articles published from 2010 to 2020 and present in databases Scopus and Web of Science.

2.4.2. Framing the process for co-developing the framework

To ensure the relevance of the proposed framework with respect to the SDGs, a co-development process was established by organizing two types of workshops with the project partners. The first workshop with 14 participants took advantage of the interdisciplinarity of the involved project partners (ranging from researchers in social sciences, environmental and process engineering, to business and technology developers in private companies and operators of public water sector utilities) to focus on developing the phrasing and definition of objectives, criteria, and indicators contained in the framework. Then, the second type of workshops took place within the so-called local communities of practice (CoPs) of the six selected demonstration cases, involving a total of 43 participants. Specifically, CoPs involved the different stakeholders with the purpose of shedding light on the relationship between SDGs and the suggested objectives, criteria, and indicators, in connection with the developed technical solutions of the given real case. As similarly carried out in the projects EviBAN and DRENSTEIN, closed questions, with possibility to openly add comments, were used in the workshops to map the perception of the relevance of each SDG to the cases and to receive feedback on the relevance of the proposed framework content (see Fig. A2 in Supplementary Materials for details on the questionnaire). A Likert scale was used for ranging the perceived relevance by the different stakeholders related to each SDG and each objective, criterion, and indicator, where 0 equalled '*not important for my application*' and 3 equalled '*very important for my application*'. The Likert scale was the only way to rate the relevance, going from 0 to 3, leaving the scores in between to be interpreted by the respondents as a linear interpolation between the minimum and maximum.

Subsequently, a second iteration on the framework content was performed based on the outcome of the CoPs and with consultation of all the research institute partners, the demonstration cases, and the involved countries in a participatory process. This resulted in the version of the framework which included the objectives, criteria and indicators which have been considered for testing the framework assessment with the demonstration cases. After having provided the framework content at its second iteration to the demonstration cases, the testing of the framework usability was carried out, leading to a third and final refinement of the framework by a core group of researchers. The steps and phases adopted for the framework development are depicted in Fig. 2.

2.4.3. Adopted approach to validate the relevance of the framework

The responses obtained through the questionnaires provided the view of the individual stakeholders. To combine the individual responses for the relevance of each SDG into one average number for each stakeholder group, the arithmetic mean was calculated. The average value will then equally include information from all the individual responses; however, no statistical properties should be inferred. The results were analysed first by plotting the SDGs relevance per each demonstration case and sorted from the highest to the lowest average value. The questions were administered through an online form where researchers, private and public stakeholders were grouped and asked to

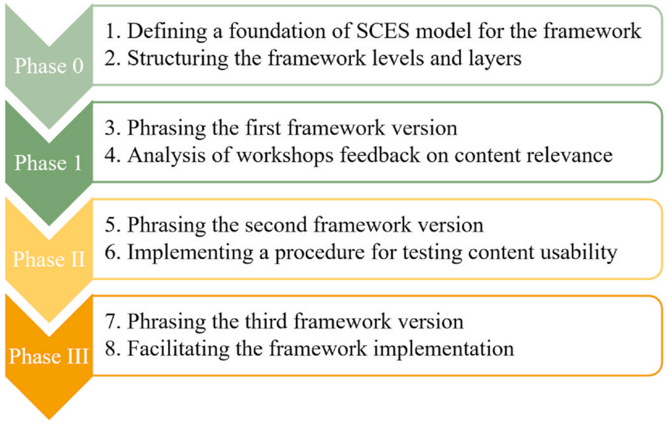


Fig. 2. The steps and phases adopted for the framework development.

express their opinion on the level of relevance of the different SDGs for their SCES (see Fig. A2 in Supplementary Materials for details on the questionnaire). In addition, Principal component analysis (PCA) and partial least squares regression (PLSR) (Martens and Næs, 2001) has been used previously in sustainability assessments (Helness et al., 2017) and were employed here to assess possible correlation in the data and whether the responses were clustered based on groups of stakeholders of the different demonstration cases. PCA and PLSR were run using a commercial multivariate analysis software, namely UnscramblerX v10.4.[4]

PCA and PLSR score and loading plots were used to assess the relevance and correlations of SDGs and the framework content for assessing the water smartness and sustainability of the demonstrated solutions. PCA and PLSR score plots support the detection of any cluster between the individual responses of a certain stakeholder and the full list of responses. PCA and PLSR loading plots contribute to find correlations between the SDGs and the objectives defined in the developed framework, highlighting whether any specific SDG is more correlated than others with the framework objectives.

The input matrixes for the PCA were the subsets of all samples with responses for SDGs, objectives, criteria, and indicators, respectively. The input matrix for the PLSR was the subset of all samples with responses for the objectives, whereas the output matrix for the PLSR was the subset of all samples with responses for the SDGs. The PCAs and PLSR were run without mean centring of the matrixes, full cross validation, and all variables were given equal weight of 1.00. In the analyses, samples that contained only missing data were excluded, with no further data preprocessing required.

2.4.4. *Adopted approach to test the usability of the framework*

The proposed framework targets the uptake of CE solutions, since it aims at enabling utilities, companies, water sector planners or decision makers to measure how water-smart a process, a product or a solution is, and how it contributes towards the achievement of the SDGs in a given case. Specifically, the framework targets a whole SCES, consisting of the four pillars detailed in Fig. 1. With such characteristics, the framework can support the decision-making process concerning the selection of alternative processes, products, or solutions.

The development of the framework included several phases as illustrated in Fig. 2. After initial development, insights for further developments of the framework in Phase II were derived through testing the usability of the framework in the demonstration cases with the approach described below, exploring how the framework was applied in different local contexts.

[4] Aspen Unscrambler (aspentech.com).

The final version of the framework is presented in the results section and included in full in supplementary materials. However, in Phase II, a test version of the framework was available with a preliminary version of user instructions for applying the framework, and a testing procedure that was set up for the demonstration cases. The steps in the testing procedure were designed to determine the indicator values, enabling data analysis procedures which can quantify the water smartness and sustainability of a given alternative of a solution under a certain scenario. The structure of the testing procedure is depicted in the following.

1. Definition of the cases and scenarios
   a. Definition of the alternative solutions
   b. Definition of the scenarios
2. Selection of relevant indicators
   a. Selection of indicators from the list in the framework
   b. Addition of important local indicators
   c. Specification of indicators if needed
3. Weighting of selected indicators
4. Data collection
   a. Identification of data sources and data availability
   b. Specification of required data processing
5. Assessment input
   a. Definition of the range for the selected indicators
   b. Definition of the thresholds for acceptable values for the selected indicators
6. Setting indicator values

To perform the implementation of the testing procedure in each case, a contact person was appointed from the research partner institution connected to each demonstration case.

3. Results

3.1. *Results of the literature search*

The performed literature search, targeting publications in the period 2010–2020, allowed to select 62 documents from the used databases. None of these documents provided a clear definition of the concept water smartness and the concept of smartness was typically related to digitalisation. In contrast, the literature for any of the identified properties of water smartness, i.e., value of water; water management; water scarcity; circularity and resource efficiency; resilience; governance; and industrial symbiosis was plentiful from a variety of sources (e.g., Cosgrove and Loucks, 2015; Topal et al., 2020).

From the literature study, the first version of the framework was developed with 21 objectives and 43 criteria covering the 5 dimensions. These were further developed through the co-development process with the stakeholder groups in the demonstration cases into the final version of the framework with 15 objectives and a variable number of criteria and indicators per objective divided in 5 dimensions (see Table 2 below and Table A3 in Supplementary Material).

3.2. *Mapping the connection between SDGs and the framework*

In the local COP workshops, the attending stakeholders were asked to rate on the mentioned Likert scale the relevance of each of the SDGs (reported with graphics in Fig. A3, in the Supplementary Material). The results from the questionnaires for each of the demonstration cases are presented in Fig. 3.

Results reflected the diverse type and number of stakeholders which varied for the different workshops. In the Italian case, the responses are the result of a group work reaching consensus on the final scoring before submitting the answers, while for the other cases the final scoring consisted in the average provided by the single stakeholders. Comparing the results for the different cases with the characteristics of the case described in Table 1 and the further details provided in section 2.3, the

Table 2
Structure of the framework, divided in five dimensions, fifteen objectives and variable numbers of criteria and indicators per objective.

Dimension	No.	Objective	Criteria (No.)	Indicators (No.)
Social (S)	S1	Maintain the social benefits provided by traditional water- and/or wastewater utilities	3	4
	S2	Provide human well-being by the recovered resources and final products of the SCES	4	6
	S3	Enhance knowledge and acceptance of the SCES, its recovered resources and final products	2	2
Environmental (En)	En1	Minimize negative environmental impacts	4	11
	En2	Preserve nature	1	2
	En3	Have positive climate effect	3	3
Economic (Ec)	Ec1	Maximise the economic value added in/by/through the SCES value chain	1	2
	Ec2	Give added economic benefits to the parties of the SCES	1	5
	Ec3	Give added economic benefits to society	2	3
Governance (G)	G1	Comply with regulations, rules, and guidelines	2	3
	G2	Contribute towards Integrated Water Management	1	4
	G3	Have participatory governance	2	2
Technical Performance (TP)	TP1	Achieve targets for traditional services provided by water- and/or wastewater utilities	5	7
	TP2	Deliver correct quality and quantity of the recovered resources and final products of the SCES	2	2
	TP3	Minimize waste and keep resources in use	1	1

responses clearly reflect the technologies developed in the different cases. In Accra, e.g., biochar is a final product, which was mirrored by the high relevance of SDG no. 7, i.e., *affordable and clean energy*. In Amsterdam, where the focus was on developing new bio-composite materials by an industry participant in the WIDER UPTAKE project, SDG no. 9 industry, *innovation and infrastructure* was scored highest for relevance by the local stakeholder group. In Prague, where the focus was on reuse of reclaimed wastewater as an alternative to drinking water for urban irrigation, the highest score for relevance was for SDG no. 12 *responsible consumption and production*, while in Sicily, Hamar and Stavanger where the main actor in the local stakeholder group was the wastewater utility, SDG no.6 *clean water and sanitation*, was seen as the most relevant SDG. The influence of the local conditions and context on the responses from the stakeholders is as expected and underlines the importance of considering the local context and involving local stakeholders in an assessment of water smartness and sustainability.

By means of grouping the results by SDG and sorting the average scores from all the responses, Fig. 4 points out that SDG 6 scored as the most relevant, being water utilities central in the selected demonstration cases, given their responsibilities for clean water and sanitation. SDG 6 is followed closely by SDG 9, highlighting the innovative aspects of the demonstrated solutions, being SDG 9 about building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation. The involved solutions are also seen as highly relevant as a method to tackle climate change and its impacts (SDG 13), make cities and human settlements inclusive, safe, resilient, and sustainable (SDG 11), and ensure sustainable consumption and production patterns (SDG12).

The score plot from the PCA used to assess correlations and clustering in the individual responses for the stakeholder groups (Fig. A4 in supplementary materials) showed that the scores on relevance of the SDGs spanned the same interval on the first principal component, which accounted for 84 % of the variation in the data, and revealed no clustering. As discussed above in section 2.4.3, no statistical properties should be inferred from the calculated average of responses on a Likert scale. However, the PCA was performed on the individual responses and demonstrated that none of the stakeholder groups scored the relevance of the SDGs clearly different from the other cases, which indicates that the overall average is a good representation for all the cases.

The researchers which structured the framework answered the same questionnaires administered within the local CoPs. The overall score for the objectives, criteria and indicators based on the responses from all the workshops, including the researchers' group is depicted in Fig. 5.

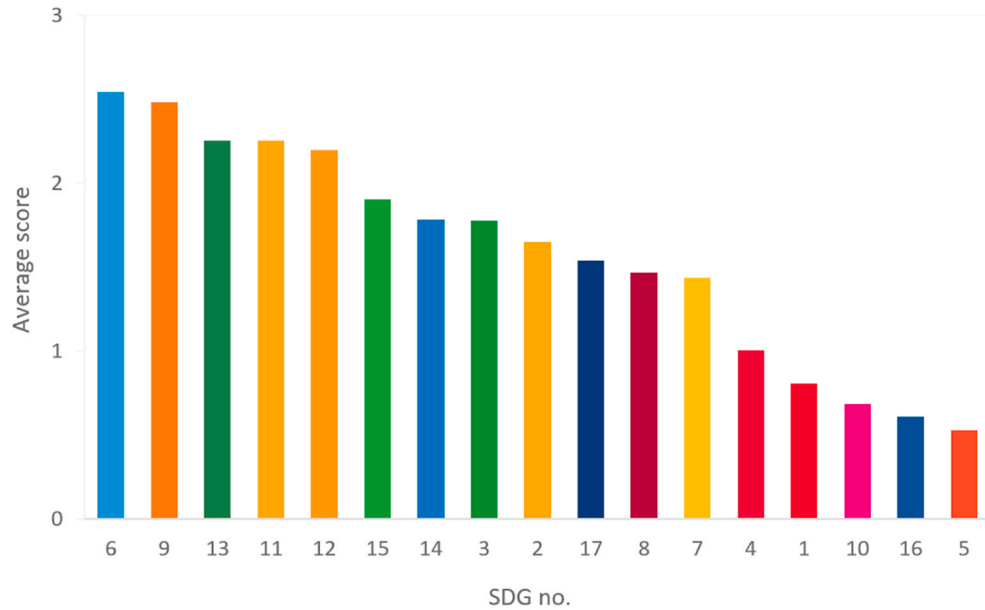
All stakeholder groups scored the relevance of the objectives higher than the criteria, and the criteria, higher than the indicators. The researchers gave a high overall score for all, with relatively small differences between the objectives, criteria, and indicators, whereas larger differences can be seen between the three levels from the perspective of the demonstration cases. This can be explained as a reflection of the local differences in the cases. The framework aims to cover a wide variety of solutions with the possibility of local adaptation, leading to differences in relevance of certain criteria and indicators. The high overall score for objectives shows that the researchers and stakeholders attending the workshops found the set of objectives suitable to assess the sustainability of their solutions. The individual scores for each objective, criterion, and indicator from each workshop were analysed to identify low scores to consider removal or rephrasing of certain segment of the framework content at the second iteration.

3.3. Validating the framework relevance through the adopted approach

The complete dataset of individual answers across the cases was analysed with PCA to explore the data for potential grouping. The score plots and loading plots for the results with respect to SDGs, objectives, criteria, and indicators are presented in Supplementary Materials (respectively shown in Figs. A4, A5, A6, and A7). Some data points were considered to reflect differences in specific conditions between cases, e. g., the Dutch case with focus on material recovery, and the Italian responses were represented by only two datapoints due to the mentioned consensus discussion. However, no data could be considered as outliers. The PCA therefore confirmed that the different stakeholder groups scored the relevance of the SDGS, objectives, criteria, and indicators in a similar way.

PLSR was used to explore the relationship between SDGs and the proposed objectives of the framework, based on the responses at the CoPs. In the analysis, the scores for relevance of the objectives in the framework were used for the input matrix, whereas the scores for relevance of SDGs were used for the output matrix. The score plot from the PLSR shows the relationship between the responses from the different demonstration cases according to the factors defined by the principal component analysis of the input and output matrixes. If the respondents from any of the demonstration case had scored the relevance of the objectives and SDGs very differently from the other cases, the PLSR score plot would show this by separating the scores from the demonstration case in a distinct group. As can be seen from the PLSR score plot shown in Fig. 6, no clear clusters appeared, pointing out that there is consistency throughout the demonstration cases on scoring the relevance of SDGs and objectives in the framework. The Italian case stands out because of the two answers resulting from the mentioned consensus

Fig. 3. The local CoPs' perception of relevance of SDGs, sorted from the highest to the lowest scores. (0 = not relevant, 3 = highly relevant).



Legend of SDGs colours:	9 - Industry, innovation and infrastructure
1 - No poverty	10 - Reduced inequalities
2 - Zero hunger	11 - Sustainable cities and communities
3 - Good health and well-being	12 - Responsible consumption and production
4 - Quality education	13 - Climate action
5 - Gender equality	14 - Life below water
6 - Clean water and sanitation	15 - Life on land
7 - Affordable and clean energy	16 - Peace, justice and strong institutions
8 - Decent work and economic growth	17 - Partnerships for the goals

Fig. 4. Overall responses on relevance of SDGs, sorted from the highest to the lowest scores. (0 = not relevant, 3 = highly relevant).

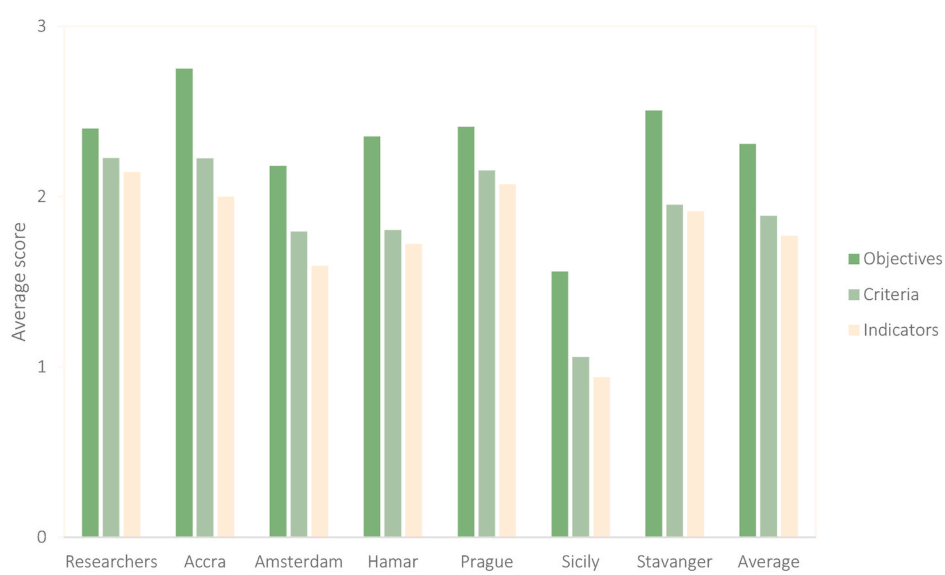


Fig. 5. Responses from the researchers' team and the CoPs on the relevance for the objectives, criteria and indicators. (0 = not important for the application, 3 = very important for the application).

discussion.

The PLSR loading plot in Fig. 7 shows three distinct groups of SDGs related to the responses on the relevance for the cases. The group in the upper left corner represents the SDGs with an average relevance lower than 1, i.e., less relevant for the applications (SDG 1, 4, 5, 10 and 16). The group in the middle are the SDGs with an average relevance

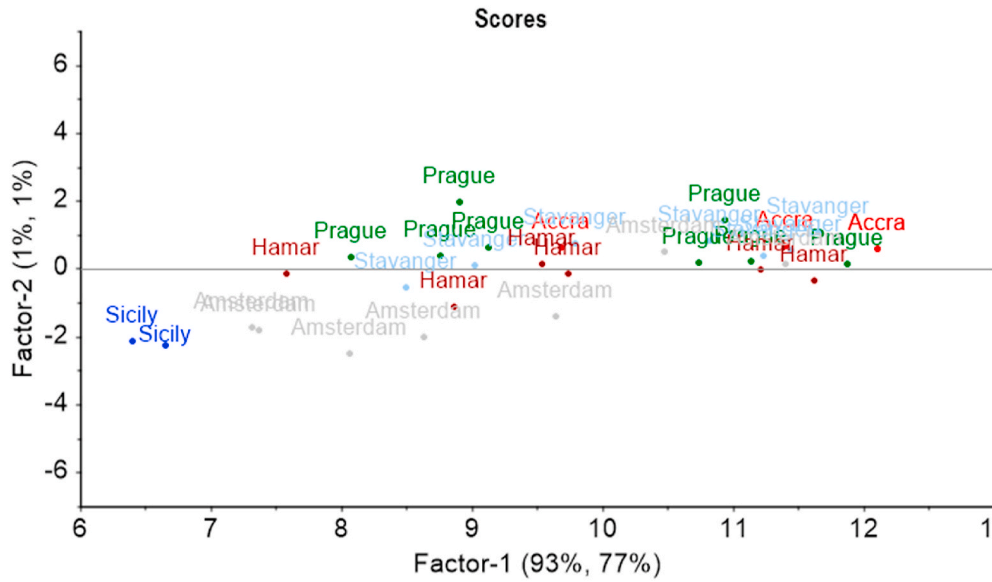


Fig. 6. Score plot from PLSR with the scores for relevance of the objectives as input and the scores for relevance of the SDGs as output.

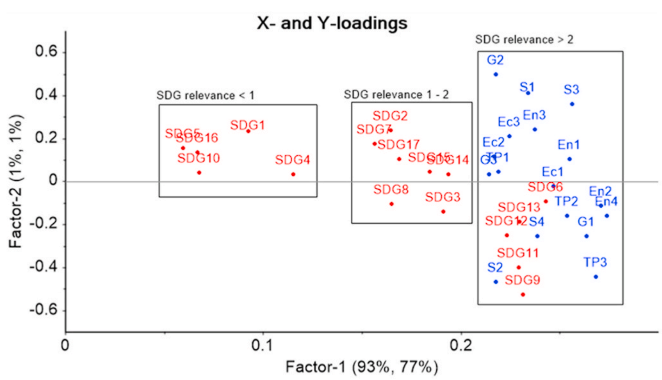


Fig. 7. Loading plot from PLSR with the scores for relevance of the objectives as input and the scores for relevance of the SDGs as output.

between 1 and 2 (SDG 2, 3, 7, 8, 14, 15 and 17). The SDGs with the highest relevance for the applications, i.e., SDG 6, 9, 11, 12 and 13, can be found in the same range of loading as the objectives in the framework.

Fig. 7 shows a correlation between the relevance of the objectives in the framework and the most relevant SDGs for the cases, indicating that the respondents represented within the dataset found the objectives relevant in connection to these SDGs.

3.4. Testing the framework usability through the adopted approach

The testing phase is associated with the second iteration on the elaboration of the framework content. The first iteration implied the definition of the framework's structure and preliminary content, as well as receiving feedback from the workshops. The outcomes of the workshops highlighted that the proposed first version of the framework was overall well aligned with relevant SDGs for the demonstration cases, still few changes were implemented at the second iteration to refine the phrasing of some objectives, criteria, and indicators of the framework content to be used for the testing. The demonstration cases undertook the proposed testing approach for applying the framework at its second iteration, starting from the definition of each own SCES and eventual scenarios.

For the definition of the SCES, the structure and pillars of the SCES reported in Fig. 1 were considered as a basis. Identifying the environmental, economic, technical, social, and administrative boundaries of a solution is crucial to properly recognize the roles of the involved stakeholders and allow the proper sharing of responsibility for assessing the different indicators composing the framework. As an example, a schematic representation of the SCES in the Hamar case (Norway) is depicted in Fig. 8, where boundaries and conceptual interactions are highlighted.

In Fig. 8, the most relevant interactions concerning the Hamar's case are included. The geographical and legislative boundaries of the Hamar SCES are related to the territory of the four Norwegian municipalities served by the WWTP managed by the partner Hias and the solid waste management facility managed by the partner Sirkula. The other types of boundaries cover environmental, economic, technical, and social aspects (having the lake Mjøsa as the receiving water body of the considered WWTP and the biogas users, Norgro company, farmers receiving Hias products, as well as commercial activities and individual citizens as societal receivers). Referring to the four pillars of the SCES, business models are mainly related to the revenues coming from selling the final products, after converting the biogas into electricity and selling fertilizers in the form of struvite to Norgro, biomass to farmers, and soil products to commercial activities and private citizens. The main stakeholders with related recovery processes and recovered resources are (a) HIAS, as the wastewater treatment manager, in charge of the traditional wastewater treatment process, (b) HIAS How2O, as the owner of the innovative process useful for the biological recovery of phosphorus, responsible for the production of struvite, and (c) Sirkula, as the sludge manager, in charge of transforming the biomass as recovered resource into soil fertilizers as final products.

During the testing, the demonstration cases were defined to different degrees according to the SCES theoretical definition, occasionally missing the conceptual integration of stakeholders, recovery process and recovered resources, business model, and applications and final products. Moreover, the definition of scenarios and related alternatives were intended to be consistent for the whole assessment of the framework. However, for some cases, the selected scenarios and alternatives were considered only for assessing multiple values of only some indicators. Scenarios and alternatives may vary from case to case, but they should hold for all the indicators selected for a given case.

All the demonstration cases performed the step of selecting relevant indicators whether the data for assessing their values was available. An overview of the indicators' selection for all cases is reported in Supplementary Materials (Fig. A8), with values 0, 1 and 2 corresponding

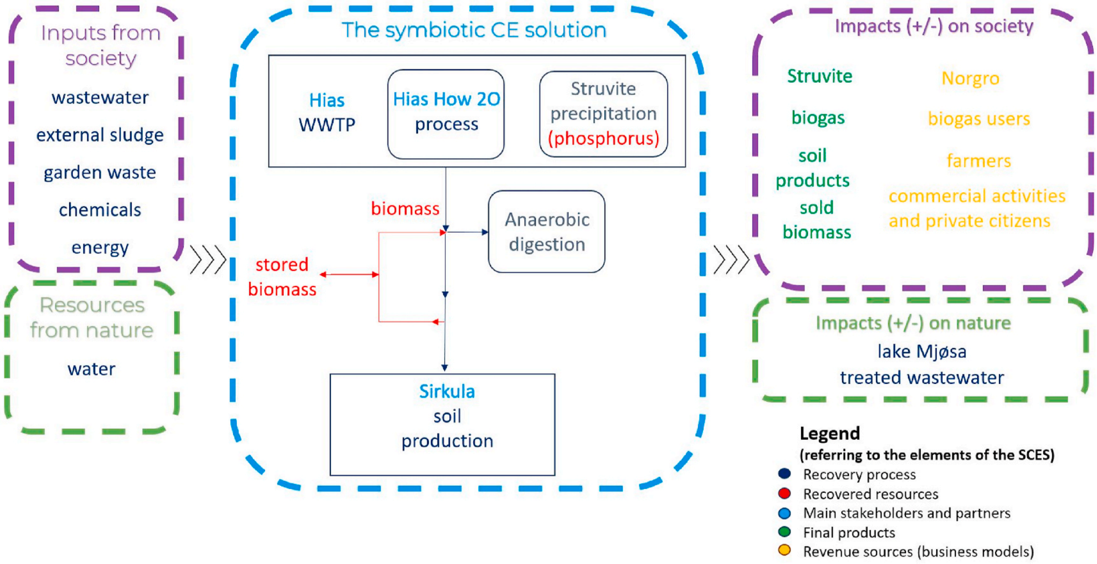


Fig. 8. Hamar demonstration case described according to the proposed SCES structure.

respectively to not selected, uncertain, and selected. Values in between these integers are due to averaging the inputs, for example when more than one scenario or alternative were involved.

All indicators were scored as relevant by one or more cases, except one. This indicator was the first one in the social dimension (indicator S1.1.1), concerning the number of people utilizing the drinking water services from the SCES, and was not relevant with the selected demonstration cases because drinking water utilities were not included in this study. However, this indicator was kept as part of the framework since the utilities interested in CE models which could use in the future the proposed framework might cover the drinking water service as a business unit.

Only the cases in Hamar and Amsterdam added local indicators during the testing of the framework. All these were in the technical performance dimension. Specifically, the Hamar case added two indicators targeting specific challenges in their process, so those can be relevant only for other cases with similar recovery processes. The Amsterdam case added three indicators reflecting the assessment and optimization of circularity and efficiency of symbiotic solutions, keeping an overall general extent, and therefore vastly applicable to other types of SCES.

The demonstration cases were asked to weight the selected indicators according to a scale from 0 to 3, having 0 for non-selected indicators, 1 corresponding to *less than average important*, 2 *to average important* and 3 to *more than average important* (as reported in Fig. A9 of Supplementary materials). The results from the weighting vary more between the cases compared to the results related to the selection of the indicators. A few cases included multiple weights per indicator, though a single weight agreed between the SCES stakeholders would have reflected more clearly the impact of each indicator on the overall SCES.

Concerning the data collection step of the proposed testing procedure, the different cases provided references to the adopted data sources and required data processing with the aim of enabling users to verify results. However, for most of the cases a more detailed list of data sources would represent an improvement to enable easier assessment in the future.

Moreover, for the values of the range and the acceptability threshold, defined as benchmark values used to assess whether the performance of a SCES on a specific indicator is considered acceptable or not, some cases failed to provide maximum, minimum or threshold values for all selected indicators. These thresholds are essential to either compare the same SCES under different scenarios and/or alternatives, track progress over time or to enable meaningful comparisons between different SCESs under similar conditions. Though, these boundary values might play a crucial role for normalizing the indicators values when monitoring the performances of a SCES over time or if more SCESs are compared in terms of overall water smartness and sustainability.

Finally, the different demonstration cases set the indicators values of the framework. A full list of values for each indicator, reflecting each relevant alternative and scenario, can provide the SCES with a proper dataset to analyze performances under different circumstances. In a few cases, the values were inserted in a fragmented manner, thus the assessment might result in poor support for the decision-making process. The content detailed in Table A2 of Supplementary Material describes the findings of each case-study and each testing step, providing critical insights into the application of the framework from the six case studies.

3.5. *The co-developed content of the framework*

In the first iteration, concerning the definition of the framework structure and its objectives, criteria, and indicators phrasing, connection to SDGs and relevance of the framework content were confirmed through the workshops and the adopted validation approach. A second iteration on the framework content was carried out, consisting in few changes on rephrasing and removal and/or addition of criteria and indicators, based on the outcome of the workshops. Once the framework was adjusted at the second iteration, its testing was executed according to the proposed testing approach, to assess the barriers for its usability in real water cases which implement CE models. The outcomes of the first and second iterations were considered by the interdisciplinary group of researchers to further improve the content of the framework, so to make it more adherent to relevant SDGs while applicable in real contexts. The full-scale implementation of SCESs implies that utilities are expected to fulfil new requirements, potentially leading to conflicts with the requirements for the traditional drinking water and wastewater services. To be sustainable and water-smart, the utilities must balance any conflicting interests and find ways to exploit the value in water without compromising their role as traditional drinking water and wastewater service providers. The framework was refined to address this type of challenge, by differentiating objectives, criteria, and indicators for a traditional service, typically focused on single functions such as wastewater treatment, and for a SCES which pursues multiple objectives including resource recovery, product development, and systemic integration in line with the CE paradigm. Another distinction applied in the framework lies in the difference between recovered resources and final products. Typically, the two categories follow different processes and regulations. The framework reflects this issue by distinguishing between the two categories in both criteria and indicators, where relevant. However, it is not always possible to differentiate between recovered resources and final products, as in the case of reuse of treated wastewater, where water is both the recovered resource and the final product of the SCES. The practical implementation of the framework in the six demonstration cases highlighted the need of accompanying the framework content with guidance on aspects such as the identification of the boundaries and interactions within a SCES, definition of scenarios and alternatives, etc. The description provided in this paper can facilitate further framework implementations. The details of the content of the finalised assessment framework are presented in the Supplementary Material. Objectives, criteria and indicators grouped by the five dimensions are shown in Tables A3, A4, A5, A6 and A7. It is recommended to refer to Table A8 in the Supplementary Material for detailed information on the indicators.

Table 2 depicts the structure of the developed framework, explicitly referring to the dimensions and objectives, while reporting the number of criteria and indicators per objective.

4. Discussion

The demonstration cases reacted differently on both the relevance of SDGs and the execution of the steps in the proposed testing approach for testing the usability of the framework. These differing responses reflected not only the diversity in technical setups and data readiness across cases but also highlighted the varying levels of stakeholder engagement and awareness of sustainability goals. Overall, the process led to useful knowledge about the required specifics to achieve a useful assessment of water-smartness and sustainability for a wide variety of SCESs in the water sector. Iterations along the development of the framework in general, and along the adopted validation and testing approaches in particular, showed to be crucial to give a solid foundation for the application of the framework for reaching meaningful results for a given solution at its maturity level. These adjustments helped tailor the framework to different operational and regulatory environments, which was critical for producing results that could inform decision-making at both strategic and operational levels. As exemplified with the cases, the framework can be adopted with several purposes at different maturity stages of a SCES, such as comparing performances of different wastewater treatment processes and products, monitoring sustainability levels over time as effect of changing regulations, or defining boundaries and responsibility to estimate indicators values, etc. These findings underscore the framework's potential not only as an assessment tool, but also as a means to support the planning, communication, and co-development of circular and water-smart strategies among diverse actors. The initial selection of indicators was performed without considering data availability, following the proposed testing approach. However, a gap existed between the indicators' relevance and the actual availability of data to calculate them, often highlighting a lack in the involvement of certain partners. Key stakeholders for the solution were identified along the definition of relevant scenarios for several cases. The Italian case reported that the work towards a clear definition of their SCES and data processing required for filling the indicators values helped to define the required activities for advancing the maturity level of their case. In the Stavanger case, testing the framework led to the exploration of potential products combined with different scenarios which might occur in the future. The cases in Prague and Amsterdam showed that the full realization of water smartness and sustainability can only be obtained through focusing on both the wastewater treatment process and the products connected with their applications. Governance aspect in the form of required rules and regulations may be a higher barrier that technology. Stakeholders with knowledge of both areas must be involved in the SCES to provide input for all objectives of the proposed framework. When these connections are not yet well established, the framework utilization would result in highlighting the areas with missing information, indicating the needed stakeholder categories to further develop the SCES towards water-smartness and sustainability. Nevertheless, since the framework is based on input from a limited number of stakeholder groups and demonstration cases, there is a risk that certain objectives, data needs, or aspects of sustainability might not be fully represented. This could lead to bias or knowledge gaps in the assessment, particularly when stakeholder input is used to evaluate the relevance of SDGs. Future applications should be aware of this limitation and consider expanding stakeholder engagement to include missing perspectives and sectors. The findings from the six case studies reveal critical insights into the application of the framework, as reported above and in Table A2. The challenges encountered in these six cases align with those reported in similar projects. For instance, the projects TRUST, EVIBAN, and B-WaterSmart all faced significant complications in applying their respective frameworks. A common barrier was the lack of organizational structures to process and analyze the data required by the indicator-based frameworks efficiently. Future applications should prioritize establishing clear guidelines for indicators specification and threshold setting to ensure more robust assessments. The limitations, the strengths and innovation of the study consist respectively in applying the same framework to various case studies at different maturity stages, the deep stakeholders' involvement for co-developing the content of the proposed framework, and the concept of SCES as the basis for establishing the boundaries when assessing the indicators. The described framework has been developed grounding its content around relevant SDGs, selected by the six demonstration cases, and around the Water Europe definition of water smartness. The values of the framework's indicators should reflect the entire SCES status or an estimation of considered alternatives or scenarios. The novel concept of SCES and its crucial role for the indicators assessment of the proposed framework mark a clear distinction from other similar frameworks which don't ground the respective assessments around the paradigm of symbiosis (Chrispim et al., 2020; Preisner et al., 2022; Sala-Garrido et al., 2023; Smol, 2023; Smol et al., 2023). Therefore, the definition of the different elements constituting a SCES plays a key role for using effectively this framework. Including the required industrial symbiosis inherently in the proposed approach is a necessary step forward for evaluating alternatives and scenarios of a new paradigm of water and wastewater solutions.

The provided list of indicators is a basis for selecting how to measure the objectives, and the selected indicators may vary between cases as there might exist several paths to be water smart and sustainable. Based on the framework which presented in this paper, the Water Smartness and Sustainability (WS&S) Index has been introduced with the purpose of evaluating the overall level of WS&S of a SCES in the water sector (Helness et al., 2024).

5. Conclusions

A new framework was developed to assess the water smartness and sustainability targeting industrial symbiosis of solutions in the water sector. By grounding the content on SDGs and the novel concept of SCES, the framework showed to enable a clear definition of the solution itself and relevant scenarios, boosting resource recovery practices in the water sector, from the water reuse for irrigation to the utilization of recovered energy, nutrients and material for urban, agriculture or industrial activities. The development, validation and testing were centred around six real case studies, with the following key findings:

- clear connection between the developed framework and the SDGs, mapped through workshops and active stakeholders' engagement.
- validation of the framework relevance, proved through structured data exploratory analysis.

- testing of the framework on different case studies, demonstrating its usefulness for diverse technological processes and under different contexts.

Overall, the application of the framework in real contexts showed to be an effective means to support the decision-making between multiple alternatives which can be adopted to enhance sustainability, heading to improved performances of social, environmental, economic, organizational, and technical performance dimensions. In particular, the shares of responsibilities of the involved stakeholders were pointed out in the different case studies, suggesting the needed directions of efforts in future developments. Finally, because of its transferability into similar application fields, the methodology described in this paper can serve as inspiration to a large audience of researchers when developing assessment frameworks concerning circular economy and sustainable development.

CRediT authorship contribution statement

Camillo Bosco: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Karen Nessler Seglem:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Edvard Sivertsen:** Writing – review & editing, Validation, Supervision. **Oriana Jovanović:** Writing – review & editing, Supervision, Data curation. **Herman Helness:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Funding

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869283.

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.

Acknowledgements

The authors desire to acknowledge all the project partners which have provided insightful feedback during the validation and the testing of the co-developed framework.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145874.

Data availability

Data will be made available on request.

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