Sustainability assessment framework for integrated seawater desalination and resource recovery

A participatory approach

Ktori, Rodoula; Palmeros Parada, Mar; Rodriguez-Pascual, Marcos; Loosdrecht, Mark C.M. van; Xevgenos, Dimitrios

DOI
10.1016/j.resconrec.2024.107954

Publication date
2025

Document Version
Final published version

Published in
Resources, Conservation and Recycling

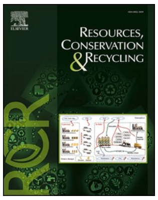
Citation (APA)
Ktori, R., Palmeros Parada, M., Rodriguez-Pascual, M., Loosdrecht, M. C. M. V., & Xevgenos, D. (2025). Sustainability assessment framework for integrated seawater desalination and resource recovery: A participatory approach. *Resources, Conservation and Recycling*, *212*, Article 107954. https://doi.org/10.1016/j.resconrec.2024.107954

Resources, Conservation & Recycling 212 (2025) 107954

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling



Review

Sustainability assessment framework for integrated seawater desalination and resource recovery: A participatory approach

Rodoula Ktori [*], Mar Palmeros Parada [1], Marcos Rodriguez-Pascual, Mark C.M. van Loosdrecht, Dimitrios Xevgenos [2,*]

Department of Biotechnology, Delft University of Technology, Van der Maasweg 9, 2629 HZ, Delft, The Netherlands

ARTICLE INFO

Keywords:
Sustainability assessment framework
Stakeholders' participation
Value-sensitive design
Desalination
Brine treatment

ABSTRACT

Valuable and rare materials in seawater brine are often discarded during desalination. However, there is an increasing focus on recovering these resources, due to the economic and environmental opportunities it can bring. Despite this shift, current Sustainability Assessments (SA) in desalination overlook the brine handling and social dimensions, and brine treatment assessments remain centered on techno-economic dimensions. This work proposes a comprehensive framework for the SA of integrated desalination and resource recovery options, focusing on recovering valuable materials from brine. The framework not only evaluates pre-defined systems but supports the identification of system features of interest, such as products to assess and technologies to include, as well as the transparent selection of indicators, considering specific contexts. To develop this framework, a review of the literature on SA in desalination and brine treatment systems was conducted. Looking at the identified gaps, we synthesized the findings and key messages and proposed the integration of Multi-Criteria Analysis and Value-Sensitive Design in the decision-making process. This allows stakeholders to be involved and incorporates their values at different stages of the assessment, making it distinct from traditional SA methods. This framework offers structured guidance to stakeholders on how to carry out qualitative and quantitative assessments while ensuring transparency in the assessment process.

Acronyms

AHP	Analytic Hierarchy Process
EIA	Environmental impact assessment
GHG	Greenhouse gas
GRA	Grey relational analysis
LCA	Life Cycle Assessment
MAUT	Multi-Attribute Utility Theory
MCA	Multi-criteria assessment
MCDA	Multi-criteria decision analysis
MCDM	Multi-criteria decision making
MLD	Minimal Liquid Discharge
RO	Reverse Osmosis
SA	Sustainability Assessment
SAW	Simple Additive Weighting
SEC	Specific energy consumption
SWRO	Seawater Reverse Osmosis
TEA	Techno-economic analysis/assessment
TLR	Technology Readiness Level
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
VSD	Value Sensitive Design
ZLD	Zero Liquid discharge

1. Introduction

Seawater desalination is one of the most crucial water treatment technologies for addressing water scarcity in water-stressed regions. This is an energy-intensive process, and besides water production, there is a residual stream called brine. Brine is often discharged into the ocean or back to the environment with various methods such as deep well injection and evaporation ponds (Panagopoulos et al., 2019). Seawater

---

[*] Corresponding authors.
E-mail addresses: r.ktori@tudelft.nl (R. Ktori), d.xevgenos@tudelft.nl (D. Xevgenos).

[1] Present address: Department of Water Management, Delft University of Technology, Stevinweg 1, 26278 ZN Delft, The Netherlands.

[2] Present address: Technology Policy & Management faculty, Delft University of Technology, Jaffalaan 5, 2628 BX Delft, The Netherlands.

https://doi.org/10.1016/j.resconrec.2024.107954
Received 17 May 2024; Received in revised form 17 September 2024; Accepted 30 September 2024

contains large amounts of valuable and rare materials (Mavukkandy et al., 2019) that end up in the brine (Ogunbiyi et al., 2021), presenting economic and environmental opportunities from their recovery through brine treatment (Commission, 2020; Xevgenos et al., 2024). Recent studies have focused on developing technologies to recover materials such as magnesium, calcium, and sodium (Mavukkandy et al., 2019; Cipolletta et al., 2021; Morgante et al., 2024), as well as metals from seawater brine (Bello et al., 2021). These efforts aim to go beyond water production, demonstrating a more substantial commitment to resource recovery and circular economy principles.

No single technology can efficiently recover all the valuable materials from seawater brine, necessitating integrated approaches tailored to specific products and conditions, with attention to the market potential of individual products (Ogunbiyi et al., 2021). For instance, the technological feasibility of such an integrated seawater desalination and brine treatment was shown in a pilot project in Lampedusa, Italy, with five unit operations integrated for the recovery of water and five high-quality products (Morgante et al., 2024). This integration can improve the technological and economic performance of desalination systems but also introduces complexities, making comprehensive sustainability assessments (SA) essential to evaluate the impacts beyond technical and economic performance (Rustum et al., 2020).

Sustainability assessment has become a rapidly developing area that supports the evaluation of emerging processes, such as the integration of desalination and brine treatment technologies, beyond traditional techno-economic analysis (TEA) (Palmeros Parada, Osseweijer and Posada Duque, 2017). Early sustainability assessments of desalination processes focused on techno-economic indicators (evaluating technical feasibility and economic performance, such as capital and operational costs, and return on investment) and brine disposal while neglecting environmental and social aspects (Afgan, Darwish and Carvalho, 1999; Hajeeh and Al-Othman, 2005). Although environmental impact assessments using methodologies like Life Cycle Assessment (LCA), which assesses environmental impacts across a system's life cycle, have been reported, their integration with techno-economic and socio-economic analyses remains limited, hindering comprehensive sustainability evaluation (Raluy, Serra and Uche, 2006; Zhou, Chang and Fane, 2013; Elsaid et al., 2020; Aziz and Hanafiah, 2021). On the other hand, in techno-economic studies, economic sustainability focuses on business economics, while environmental is often limited to GHG emissions (Micari, Moser, et al., 2020). The environmental assessments and LCAs need to be combined with techno-economic (Mezher et al., 2011) and socio-economic analysis to reduce uncertainties and incorporate a broader range of parameters (Ibrahim et al., 2018; Lee and Jepson, 2021; Sola, Sáez and Sánchez-Lizaso, 2021). There is no sustained progress in one pillar (dimension) without progress in all (Sala, Farioli and Zamagni, 2013).

Despite advancements in SA frameworks for desalination processes over the past decade, incorporating more comprehensive three-dimensional assessment (Lior, 2017; Ibrahim et al., 2018; Wang et al., 2019), there remains a notable gap in consideration of brine and resource recovery within existing frameworks. Previous studies focusing on the assessment of water and salt recovery from brine have often overlooked the social aspect, with environmental assessments primarily focused on emissions from energy consumption (Micari, Moser, et al., 2020; Panagopoulos, 2021b; Morgante et al., 2022) and environmental impacts from brine disposal into the marine environment (Xevgenos et al., 2021). Existing studies have typically centered on either desalination or zero liquid discharge (ZLD) systems, failing to provide a comprehensive evaluation of integrated desalination and brine management approaches. Moving towards brine minimization and resource recovery systems, the existing frameworks need to be updated. To address the gap, we formulate the following question:

> *How can SA methodology be tailored to ensure comprehensive evaluation and stakeholder participation in multi-objective systems of integrated desalination and brine management?*

To answer the research question, this work aims to develop a methodological approach to assess the sustainability performance of extended treatment chains aiming to achieve resource recovery in the desalination industry. While seawater desalination is used as a primary example, the principles and steps outlined in our framework can be applied to various water sources, making it a robust tool for sustainability assessment across diverse desalination processes.

This work is organized as follows: Section 2 provides the theoretical foundation for developing the assessment framework. Section 3 presents the methodology for the literature review and the development of the assessment framework. Section 4 presents an extensive literature analysis of assessment frameworks for desalination and brine treatment systems (Section 4.2.1) a review of the available assessment indicators (Section 4.2.2), and a literature analysis of assessment frameworks and decision-support tools on resource recovery from other sources (Section 4.2.3). Drawing on the theoretical background of SA, key insights, and research gap, an assessment framework is developed and presented in Section 4.3. Finally, Section 5 discusses the impact and limitations of this study and future work. The developed indicator database is provided in Supplementary Information I.

2. Theoretical background on sustainability assessment and multi-criteria assessment

Sustainability assessment guides decision-making towards sustainability (Bond, Morrison-Saunders and Pope, 2012), encompassing both negative impacts and positive contributions across various dimensions. Ness et al. (2007) defined SA as a method that provides decision-makers with "*an evaluation of global to local integrated nature–society systems in short and long term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make society sustainable*". SAs are critical tools used to evaluate the sustainability of various systems and processes, typically applied to compare the sustainability of two or more systems, whether they be technologies, processes, or entire organizations. The eligibility for SA usually depends on the availability of relevant data and the defined indicators that measure sustainability aspects such as environmental impact, economic viability, and social equity (Gasparatos, El-Haram and Horner, 2008). SA has also the role of improving the decision-making process by:

- Integrating sustainability dimensions and considering their interdependencies.
- Including intragenerational and intergenerational considerations.
- Supporting constructive interaction among stakeholders
- Accounting for uncertainties (Gasparatos, El-Haram and Horner, 2008; Cinelli, Coles and Kirwan, 2014)
- Managing trade-offs, prioritization, comparability, and compensation between sustainability categories (Lindfors, 2021).

Traditional sustainability assessments relied on reductionist methods (Gasparatos, El-Haram and Horner, 2008), using one measurable indicator, one dimension, a single scale of analysis, one objective, and a one-time horizon (Munda, 2006; Gasparatos, El-Haram and Horner, 2008). However, there is now a move towards more indicator-based assessments, which offer a more comprehensive understanding of sustainability. Indicator-based SA, such as multi-criteria assessment (MCA), is the most commonly used because "*They can translate physical and social science knowledge into manageable units of information that can facilitate the decision-making process*" (UN, 2001; Gasparatos and Scolobig, 2012).

MCA is a methodology used to evaluate and prioritize different options based on multiple criteria (Herva and Roca, 2013), considering multiple sustainability dimensions, stakeholders' values, and uncertainties (Cinelli, Coles and Kirwan, 2014). MCA frameworks vary from simple to sophisticated methods, including horizontal or soft MCA, which aims to structure knowledge for decision support, requiring very little information, and vertical or hard MCA, which uses mathematical programming techniques for ranking alternatives, requiring extensive information (Mendoza and Martins, 2006; Herva and Roca, 2013). The key elements identified in traditional MCA are scope definition (including selection of alternatives), criteria selection, and interpretation methods (assigning weights, aggregating scores and ranking alternatives) (Kumar et al., 2017; Lindfors, 2021). For more detailed methodological insights, readers can refer to works by Sala, Ciuffo and Nijkamp (2015), Lindfors (2021), and Gasparatos and Scolobig (2012).

The technical dimension is often included indirectly in the evaluation of well-developed technologies, but directly for emerging technologies to assess the performance and feasibility of the process (Ren et al., 2020; Lindfors, 2021) since the operational performance is uncertain (Lindfors, 2021). Technical aspects significantly influence economic, environmental, and social dimensions (Ren et al., 2020; Wreyford et al., 2020). Thus, SA must integrate economic, environmental, social, and technological issues and their interactions and consider the consequences of present actions into the future and drivers of change (Gasparatos, El-Haram and Horner, 2008; Pintér et al., 2012). This integrated approach is particularly valuable in desalination and brine treatment projects aiming at resource recovery, where technologies are relatively new, and cost, environmental impact, and resource recovery potential need to be balanced.

Moving towards interdisciplinary and trans-disciplinary approaches underscores the necessity of integrating methods, concepts, and theories from various disciplines and effectively engaging stakeholders (Sala, Ciuffo and Nijkamp, 2015). Stakeholder participation is crucial for aligning resource recovery innovations with their socio-technical context, democratizing decision-making, and ensuring the relevance of sustainability assessments (Hamilton et al., 2015; Palmeros Parada et al., 2022). Stakeholder participation goes beyond merely incorporating expert opinions in the weighting process of decision-making studies, empowering stakeholders and providing them with the opportunity to understand the problem and influence the decision (Hamilton et al., 2015).

Value-sensitive design (VSD) is a participatory approach that proactively incorporates societal values (Miller et al., 2007) into technological designs by investigating stakeholder values and identifying desirable technical features (Friedman, Kahn and Borning, 2015, 2017). In particular, VSD incorporates social aspects into emerging technologies consciously (van den Hoven, Vermaas and van de Poel, 2015), which are often developed in processes that are blind to the context and the stakeholders' realities (Palmeros Parada, Osseweijer and Posada Duque, 2017). This inclusive design process allows stakeholders to co-design technologies that align with their values, perceptions, and expectations (Palmeros Parada et al., 2022). It is a valuable methodology for ensuring stakeholder participation and comprehensive evaluation in addressing multi-objective systems.

While VSD has been utilized in various contexts, such as ICT and robotics projects (Davis and Nathan, 2016), the design of biorefineries (Palmeros Parada et al., 2020), wind turbines and wind parks (Oosterlaken, 2014), and digital platforms (de Reuver et al., 2020), its application in the water and wastewater sectors remains limited. Only an approach based on VSD has been used to proactively integrate societal values in the design of technologies for resource recovery and gain first insights into its societal implications in the context of small islands (Palmeros Parada et al., 2023).

3. Methodology: developing the conceptual framework

To develop an assessment framework and answer the research question, a literature review was conducted as a "preparation". The key results were gathered and analysed. The findings and key messages from the literature review were composed to develop the proposed framework (synthesis phase) according to the methodology in Fig. 1.

3.1. Preparation phase

The review was conducted through various steps, as described in Fig. 1, and with a focus on:

1) Sustainability assessment methodologies,
2) Multi-criteria assessment for sustainability assessment,
3) The available assessment methodologies for desalination and brine treatment systems.
4) The available assessment methodologies for resource recovery from wastewater effluent

The literature search was conducted using Scopus and Google Scholar databases, focusing on recent publications in English. Keywords such as "MCA for SA", "sustainability assessment of desalination and brine treatment", "environmental assessment of desalination and brine", and "techno-economic assessment of desalination and brine treatment" were utilized. Additionally, terms like "sustainability assessment of ZLD", "sustainability assessment of Minimum Liquid Discharge", and "techno-economic assessment of ZLD" were included to capture relevant studies. Grey literature was excluded to maintain a focus on peer-reviewed sources, ensuring scientific rigor and reliability. The review process does not delve into the discussion of specific desalination and brine treatment technologies.

After the initial screening, studies were selected and analysed based on their relevance to (1) applicability to the context of desalination, brine management, and resource recovery, (2) alignment with sustainability assessment dimensions, and (3) multi-criteria assessment methods. Snowballing techniques, including backward and forward citation tracing, were also employed to ensure comprehensive coverage.

The literature review has been expanded to encompass fields beyond desalination, such as those of resource recovery from sources other than seawater, using snowballing. Given that resource recovery in desalination is still emerging and the assessment of such systems is in its developmental stages, insights and experiences gained from more established fields could prove very useful in developing an assessment framework for desalination.

A review of indicators for evaluating desalination, brine treatment systems, or water treatment systems was conducted. This included dimensions and indicators from the previous steps, as well as studies on LCA, environmental impact assessment (EIA), energy assessment, techno-economic, and social life cycle assessment studies. The review also covered multi-criteria or sustainability assessment tools for wastewater, urban water systems, and the water industry, in general. The search was extended to specific articles or topics identified in the reviewed literature. The relevant indicators were collected using the same criteria of relevance.

3.2. Analysis phase

After the preparation phase, the most relevant studies were selected for analysis based on the above criteria of relevance. Firstly, the key elements regarding the methodological approach for SA and MCA were scrutinized. The importance, which means how vital each step is, and the order, indicating the sequence in which these elements should be followed, were evaluated. The studies were qualitatively assessed in terms of sustainability principles, transparency, and consideration of sustainability dimensions. Then, they were analysed based on the assessment's purpose and the methods or combinations of methods used. Transparency in this phase means openly sharing procedural steps, providing required data, and clearly explaining decisions, such as the selection of indicators. This allows others to replicate the study, verify its findings, and hold the process accountable. Finally, stakeholder

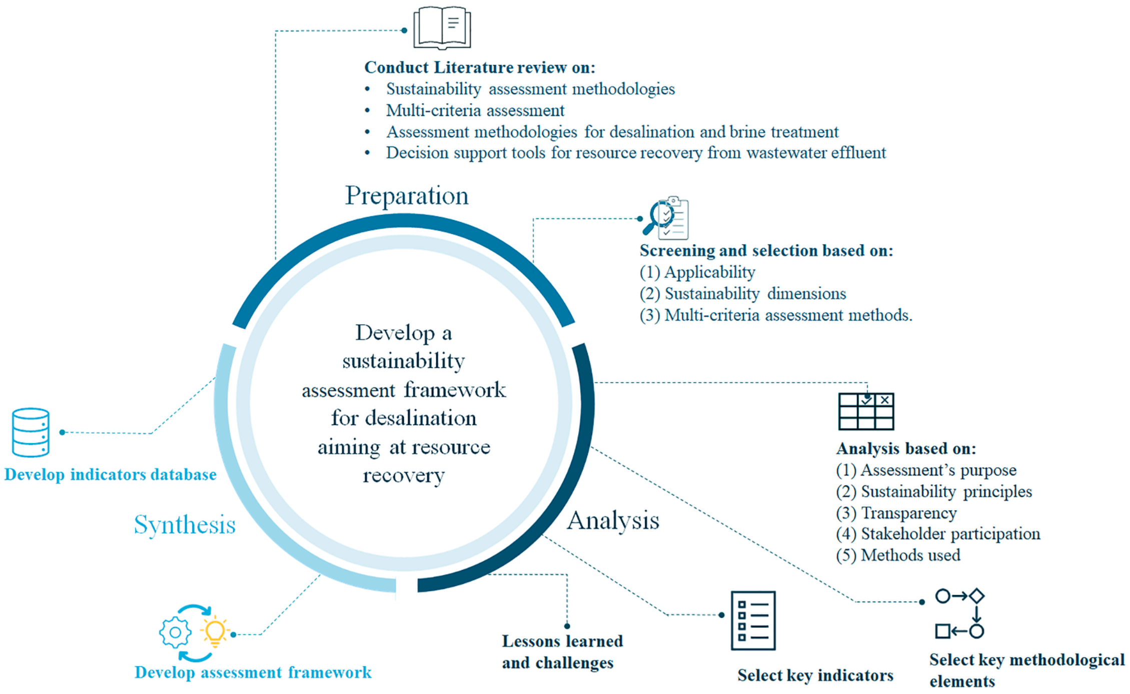


Fig. 1. Scheme of research methodology to develop sustainability assessment framework.

participation was evaluated by analysing which stakeholders were considered relevant, their knowledge background, how they were selected, and how and in which phases they were engaged.

3.3. Synthesis

In this phase, we synthesize the findings and key messages from the literature review into a framework for multi-criteria SA of desalination for resource recovery. As a result, the proposed framework was developed, drawing inspiration from sustainability science and building on the key elements of multi-criteria sustainability methodologies (Foxon et al., 2002; Azapagic and Perdan, 2005a, 2005b; Singh et al., 2012; Gargalo et al., 2016; Kehrein et al., 2020; Lohman et al., 2023), the review of current assessment frameworks for desalination and brine treatment, and research gaps. Additionally, elements identified as promising for a non-reductionist approach to SA in desalination and resource recovery were combined into a framework (see Fig. 2) that thus draws from value-sensitive design (VSD) and MCA (as an SA approach). This work integrates VSD elements into different steps of the proposed framework. Specifically, key characteristics of VSD, such as stakeholders' values and value tensions, will be used in the selection of the assessment indicators and design of alternative scenarios and contribute to the system's assessment and design. By incorporating values into the assessment process, we can ensure that the selected criteria and indicators are relevant and meaningful to the stakeholders involved and that the assessment addresses the real concerns and ambitions of those affected by the decisions. The order of the key elements that compose the framework was adjusted to enhance transparency in the selection of indicators and alternatives and address social challenges to overcome the weak points of the existing methodology.

Transparency is one of the key elements of an objective SA framework and can ensure credibility (Sala, Ciuffo and Nijkamp, 2015). Lindfors (2021) emphasized the need to enhance methodological transparency by providing insights into the selection of alternatives, dimensions, and indicators. The proposed framework addresses this issue by explicitly outlining the procedures for selecting assessment indicators, which are then disclosed as part of the presented results. Additionally, VSD's participatory approach enhances transparency in indicator selection and scenario design, which is particularly valuable given the frequent lack of detailed explanations for selected indicators or alternative scenarios in the literature.

Finally, within the synthesis phase, a database with 208 performance indicators has been developed (see Supplementary Information I) for a comprehensive assessment of desalination and brine treatment systems. The developed database gives an overview of the most used indicators in the field, and it can help users select the most applicable performance

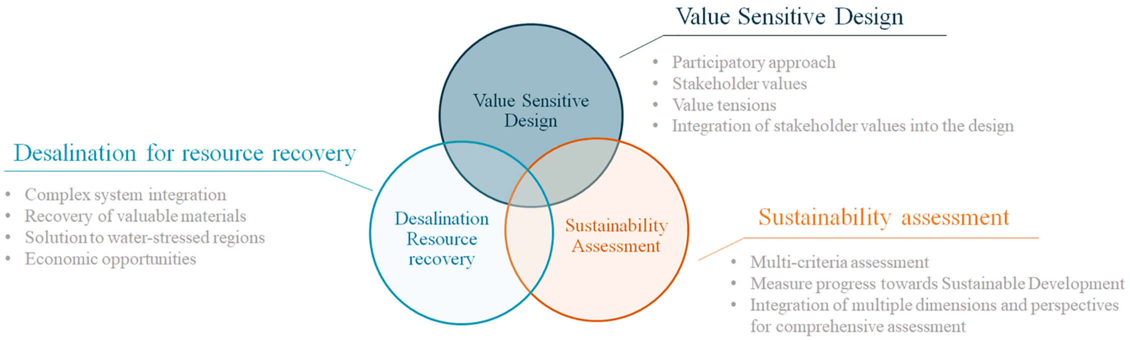


Fig. 2. The intersectionality of value sensitive design, sustainability assessment and desalination aiming at resource recovery.

indicators. The indicators are categorized into technical, economic, environmental, and social, focusing solely on a plant's planning and operation phase. It includes both qualitative (e.g., reliability) and quantitative (e.g., water recovery) indicators, along with the tools or methodologies in which they are utilized.

Please refer to Supplementary Information III (see Section A) for a more detailed explanation of concepts like value and value tension, along with examples. The supplementary information includes comprehensive definitions of the terminology used in this work.

4. Results and discussion

4.1. Preparation: sustainability assessment trends and indicator utilization in the desalination field

The research interest in sustainability assessment for the desalination field has grown over recent years (see Fig. 3), driven by global capacity expansion, cost reduction, environmental concerns around desalination and significant technological developments in brine valorisation. However, despite this growing interest, the number of publications specifically addressing sustainability assessment for brine treatment remains notably low, indicating a field ready for further exploration and research. On the contrary, there has been a significant increase in scientific publications focusing on the environmental impacts of desalination or brine treatment, particularly over the last decade. This trend underscores the growing recognition of environmental concerns associated with desalination processes, likely influenced by advancements in brine management technology and heightened awareness of brine disposal issues.

A detailed review of the literature reveals a marked imbalance in the application of sustainability indicators: while technical (91 %) and economic (100 %) indicators are extensively employed, environmental (61 %) and social (48 %) indicators fell behind. This imbalance raises questions about the comprehensiveness of current assessment methodologies in the field and underscores the need for a more balanced approach that incorporates economic, technical, environmental and social indicators into the assessment process.

Currently, only 35 % of the studies employ the three sustainability dimensions (economic, environmental, and social), indicating a significant opportunity for methodological enhancement. Incorporating social and environmental indicators enhances the overall understanding of the impacts and benefits associated with desalination and brine treatment projects, enabling stakeholders to make more informed decisions. Details of the empirical analysis that informed these adaptations are available in Supplementary Information II.

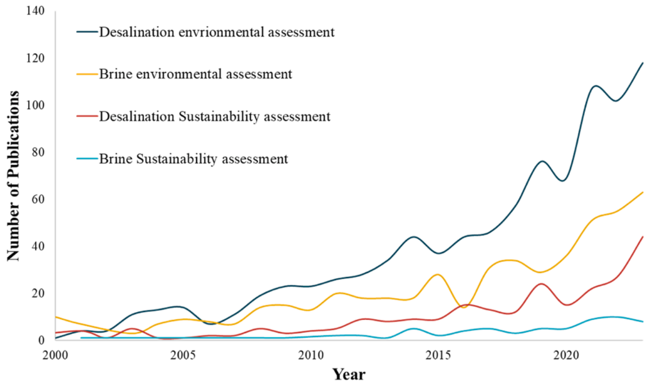


Fig. 3. The number of publications related to sustainability assessment for desalination and brine management from 2000 to 2023. Data was obtained from SCOPUS Database using the following keywords: "sustainability assessment AND brine ", "sustainability assessment AND desalination", "brine AND environmental assessment", and "desalination AND environmental assessment".

The dominance of technical and economic indicators in desalination assessments may be due to the lack of standardized methodologies and the complexity of social and environmental impacts (Lior, 2017; Lior and Kim, 2018). Unlike technical and economic dimensions, social and environmental indicators are still challenging to quantify consistently in desalination and brine treatment domains. Additionally, the limited availability and accessibility of relevant data (Ghassemi and Danesh, 2013) contribute to their limited use, as they require extensive data collection and active stakeholder engagement.

4.2. Analysis

4.2.1. Review of current assessment frameworks/methodologies for desalination and brine treatment

This section reviews the assessment approaches used in examining the sustainability of desalination systems and later brine treatment systems. Early sustainability assessments of desalination processes focused on techno-economic indicators and brine disposal while neglecting environmental and social aspects (Afgan, Darwish and Carvalho, 1999; Hajeeh and Al-Othman, 2005). Over the last decade, more comprehensive SA frameworks for desalination processes have emerged, as summarised in Table 1 and illustrated in Fig. 3.

Many SA methodologies have historically involved only a small group of experts in the identification and weighting of indicators, lacking robust stakeholder participation. For instance, Ghassemi and Danesh (2013) developed a multi-criteria decision-making model that considers environmental, technical, and economic indicators, but overlooked social indicators. Similarly, Lior and Kim (2018) and Ibrahim and Ibrahim (2018) proposed methodologies to evaluate desalination processes, addressing economic, environmental, and social issues but limiting stakeholder engagement to data collection and weight determination. Abdulbaki et al. (2020) proposed a multi-criteria decision-making tool for the optimum selection of seawater desalination technology using technical, economic, environmental, and social criteria, involving experts only in weighting via survey. Limited stakeholder engagement can result in biased outcomes and reduce the assessment's applicability. The process of assigning weightings to different indicators lacks uniformity across studies, leading to inconsistent results. Wang et al. (2019) proposed a methodology for the SA of desalination processes under hybrid information, focusing on improving weighting and sustainability ranking through integrated techniques. However, the selection of indicators and their weightings often lacked transparency, and stakeholder involvement, which could result in biased outcomes. This variability underscores the need for standardized approaches to ensure comparability and reliability across different studies.

Recent contributions have continued to advance the field. Wreyford et al. (2020) emphasized the importance of stakeholder interactions, expert input, and case-specific contextual effects in the assessment and final decision-making. Similarly, Rustum et al. (2020) provided a well-described case study and indicator selection. However, stakeholders (experts) are involved only in the ranking process.

Until this stage of the review, brine has received limited attention, mainly as a waste stream. The above studies have not considered brine valorisation or the impact of brine disposal methods. Recent research has explored the value of recovered products from ZLD systems. However, the assessment of those systems has primarily focused on TEA (Xevgenos, 2016; Mansour et al., 2018; Chen et al., 2021; Panagopoulos, 2021c, 2022). In particular, Shende et al. (2021) evaluated ZLD systems based on economic, technical, and administrative indicators, but environmental and social criteria were not considered in the assessment, focusing instead on integrating essential tools with decision-making tools, and experts were involved only in the weighting procedure.

Although not targeting sustainability assessment per se, Xevgenos et al. (2024) developed a transparent methodology for brine valorization, estimating the value that can be captured by treating the brine with a novel brine treatment system.

Table 1
Summary of literature findings on Sustainability Assessment frameworks in the desalination and brine treatment field.

Study reference	Methodology and MCDA method	Dimensions considered	Context	Stakeholder participation and social relevance	Main limitations
(Afgan, Darwish and Carvalho, 1999)	Techno-economic analysis	Technical, economic and environmental	Desalination	Stakeholders considered as data sources	Limited consideration of social aspects
(Hajeeh and Al-Othman, 2005)	Multi-criteria decision-making with AHP	Technical, economic and Environmental	Desalination	Experts involved in the weighting procedure	Lack of social dimensions, stakeholder participation
(Lior and Kim, 2018)	Multi-criteria decision-making with AHP	Economic, environmental, social	Desalination	Stakeholders involved in the weighting procedure	Poor stakeholder participation
(Ibrahim et al., 2018)	Multi-criteria decision-making with AHP, Swing	Techno-economic, environmental, social	Desalination	A diverse group of stakeholders involved in the data collection and weighting procedure	Poor stakeholder participation
(Wang et al., 2019)	Multi-criteria decision-making with AHP and TOPSIS	Techno-economic, environmental, social	Desalination	No diverse group of stakeholders, Stakeholders involved in the weighting procedure	Limited transparency in indicator selection
(Ghassemi and Danesh, 2013)	Multi-criteria decision-making with fuzzy-AHP and TOPSIS	Environmental, technical, economic	Desalination	A small group of experts involved in indicator identification and weighting procedure	Lack of social dimension
(Wreyford et al., 2020)	System-level decision support tool	Technical, economic, environmental	Desalination	Experts involved in indicator selection	Expand the model to address brine management
(Rustum et al., 2020)	Multi-criteria decision-making with fuzzy model	Environmental, economic, social	Desalination	Experts involved in the ranking procedure	Limited stakeholder involvement
(Abdulbaki et al., 2020)	Multi-criteria decision-making	Technical, economic, environmental, social	Desalination	Experts involved in the weighting procedure	Limitations in applying MCDM-based solutions, Lack of data
(Saleh and Mezher, 2021)	Multi-criteria decision-making with AHP	Economic, environmental, social	Desalination	Experts involved in the weighting procedure	Lack of data, Recommendation for the introduction of more metrics highlighted
Micari, Moser, et al. (2020)	Techno-economic assessment	Technical, economic, environmental	Brine treatment	No stakeholder participation	Lack of social dimension and stakeholder participation, the technical assessment includes only the energy requirements.
(Panagopoulos, 2021a)	Techno-economic assessment	Technical, economic	Brine treatment and resource recovery	Experts involved in the design	Lack of environmental and social dimensions, lack of stakeholder participation
(Mansour et al., 2018)	Cost assessment	Economic	Brine treatment	NA	Only economic dimension, lack of stakeholder participation
(Nayar et al., 2019)	Techno-economic assessment	Technical, economic	Brine treatment and resource recovery	NA	Lack of environmental and social dimensions, lack of stakeholder participation
(Shende et al., 2021)	Multi-criteria decision-making with AHP and grey relational analysis (GRA)	Technical, economic, administrative (social)	Brine treatment	NA	Lack of environmental dimensions, lack of stakeholder participation
(Xevgenos, 2016)	Techno-economic assessment	Technical, economic, social	Brine treatment and resource recovery	NA	Lack of environmental dimensions, lack of stakeholder participation
(Panagopoulos, 2021c)	Techno-economic assessment	Technical, economic	Brine treatment	NA	Lack of environmental and social dimensions, lack of stakeholder participation
(Micari, Cipollina, et al., 2020)	Techno-economic assessment	Technical, economic	Brine treatment and resource recovery	NA	Lack of environmental and social dimensions, lack of stakeholder participation
(Morgante et al., 2022)	Techno-economic assessment	Technical, economic	Brine treatment and resource recovery	NA	Lack of environmental and social dimensions, lack of stakeholder participation

AHP: Analytic Hierarchy Process; TOPSIS: Technique for Order Preference by Similarity to an Ideal Solution.

Micari, Moser, and Moser (2020) proposed a methodological approach for identifying suitable treatment chains based on technical, economic, and environmental analysis. The technical analysis includes only the energy requirements, and the environmental study is limited to the CO_2 emissions due to the energy consumption (operational CO_2 emissions). In addition, Micari, Cipollina, et al. (2020) performed a TEA of brine treatment to identify the most feasible and less energy-intensive system. The analysis is oriented toward salt production, not water production, and introduces a novel parameter, the levelized cost of the NaCl crystals.

Panagopoulos (2021a) performed a TEA of a seawater ZLD system, focusing on freshwater, mixed solid salt, and high-purity NaCl production. (Morgante et al., 2022) studied the economic feasibility of a novel treatment chain, highlighting the added value of recovering multiple high-quality products from seawater desalination brine. Their economic assessment used two main indicators: the levelized cost of the individual products and the brine treatment-specific cost. However, the environmental and social aspects and the impact of technical aspects on the environment were not included in the analysis.

While some efforts have incorporated environmental indicators (Micari, Moser, et al., 2020; Xevgenos et al., 2021; Panagopoulos, 2021b; Morgante et al., 2022), comprehensive sustainability assessments of ZLD systems remain scarce. A first attempt to integrate social aspects into the analysis/evaluation of desalination and brine management systems was proposed by Tsalidis et al. (2023) through social LCA.

Few studies attempted to evaluate integrated desalination and brine treatment systems with technical and economic criteria. For instance, Nayar et al. (2019) presented a TEA of an integrated Reverse osmosis (RO), electrodialysis and crystallizer to treat seawater, aiming at salt production. The added value of salt production is included in the analysis. Panagopoulos (2021b) evaluated the desalination system RO integrated with brine treatment technologies (brine concentrator, brine Crystallizer), using technical, economic, and environmental (only CO_2 emissions) criteria. The performance of the system was analysed with respect to both water and salt.

4.2.2. *Review of assessment indicators*

This section examines the key findings from the review of sustainability assessment indicators commonly used in desalination and brine treatment systems, focusing on their suitability, challenges, and insights from the literature.

The **technical dimension** aims to evaluate the technical performance of a system. A good understanding of the process is essential (Lior, 2017), particularly when integrating multiple technologies. Even with high Technology Readiness Level (TRL) technologies, performance evaluation offers insights into the improvements/optimization of the system. In reported studies, the technical aspect is often combined with the economic and typically limited to the energy requirements of the technologies, overlooking more specialized technical indicators. This may be due to the assumption that the systems are already optimized. However, the technological dimension encompasses more than energy usage, including system efficiency and technology integration. However, limitations exist, as some indicators are overestimated with respect to others because of the availability of data (Saleh and Mezher, 2021).

Regarding the energy-related indicators (in the technical dimension), the energy consumption of the process or the specific energy consumption are two of the most used indicators found in the literature. Indicators to evaluate the integration of the desalination or brine treatment systems with renewable energy systems are rarely considered, though the technical feasibility of using renewable energy sources to cover the energy requirements of the desalination sector. On the other hand, the direct impact of energy use is measured extensively with environmental indicators such as GHG intensity.

The **economic dimension** aims to evaluate the economic performance of the studied systems. All the reviewed studies include economic indicators in their analysis, which underlines that the economic aspect has historically dominated decision-making (Lior, 2017). Various indicators with similar outcomes have been used in the economic analysis of desalination or brine treatment systems, such as levelized cost, unit cost, treatment cost, and production cost. Levelized cost is defined as the sum of annual operational costs and capital investment, divided by the production capacity (Papapetrou et al., 2017). It represents the break-even price of the main product, taking into account revenues from by-products (Micari, Moser, et al., 2020). Unit cost is defined as it reflects the cost per unit of desalinated water, encompassing capital, operation, maintenance, and fuel costs (Afgan, Darwish and Carvalho, 1999; Mohsen and Al-Jayyousi, 1999; Xevgenos, 2016; Panagopoulos, 2021b). The normalization to production capacity, used in both levelized cost and unit cost calculations, ensures that comparisons are based on standardized units of output, allowing for clearer assessments of economic efficiency and scalability across various water production methods (Papapetrou et al., 2017).

Treatment cost, utilized by Xevgenos (2016) and Bick and Oron (2005), considers capital costs, energy costs, and operating costs. Wang et al. (2019) and Panagopoulos (2021c) employed production cost, however, its specific definition and the formula were not provided. The main difference is that levelized cost includes revenues from by-products, while unit cost, treatment cost, and product cost do not. Unit cost and treatment costs primarily focus on energy expenses (fuel costs). Further exploration into the economic value of seawater desalination brine effluent was conducted by Xevgenos et al. (2018), considering the potential value of the main compounds that can be recovered from the brine. Recently, the economic impact of brine treatment has been calculated as brine treatment-specific cost (Micari, Moser, et al., 2020) for ZLD/MLD systems. However, the costs of brine disposal are usually excluded from the analysis.

The **environmental dimension** aims to evaluate the effects of desalination and brine treatment processes on the environment. It is well known that the main environmental impacts of desalination are associated with high energy consumption and brine disposal. Only 61 % of the reported studies used environmental indicators, with36 % assessing CO_2 emissions from the operation, such as CO_2 emissions/m^3 of desalinated water (Lior and Kim, 2018) or CO_2 emissions/m^3 of brine (Micari, Moser, et al., 2020). The carbon footprint can be considered one of the simplest ways to measure the environmental impact of a process, and it can give an excellent first insight.

Regarding brine, limited efforts have been made with 60 % of the sustainability assessments for desalination processes, including the brine disposal in the analysis (Saleh and Mezher, 2021), often without detailed analysis. Notably, brine disposal or minimization is typically not included in the environmental assessment of ZLD or MLD systems. The main indicators found in the literature are the pollution potential from brine disposal (Lior and Kim, 2018; Saleh and Mezher, 2021), eco-toxicity (Meneses, Pasqualino and Raquel, 2010; Zhou, Chang and Fane, 2013; Balfaqih et al., 2017; Ibrahim et al., 2018), and increased salinity and temperature (Lior, 2017; Ibrahim et al., 2018).

The use of chemicals is directly related to environmental impacts in the desalination sector; however, it is not considered in the reviewed works. While Lior (2017) referred to chemical consumption in the economic assessment, it was not included in their subsequent work where the proposed framework was implemented (Lior and Kim, 2018). Similarly, Bick and Oron (2005) estimated the cost of chemicals in the economic assessment of the system but not in the environmental assessment.

The **social dimension** aims to evaluate the effect on the local community and the employees (Lior, 2017). Only 48 % of the reported studies used social indicators, with 45 % assessing impacts on the local economy and communities (Lior, 2017; Ibrahim et al., 2018; Panagopoulos, 2021b). These studies considered indicators such as the level of aesthetic acceptability, noise levels, provision of employment opportunities, safety levels, quality of life, and effectiveness and equity of employment. Xevgenos (2016) recommended the indicator of willingness to pay. Water quality was used in 25 % of the studies to assess social-technical aspects (Saleh and Mezher, 2021). Shende et al. (2021) included the operational complexity of the processes as a social indicator, reflecting the need for skilled labour. Similarly, Wang et al. (2019) emphasized the importance of specific expertise, and Panagopoulos (2021b) highlighted the significance of high-skilled employees and specialized knowledge. Loutatidou et al. (2017) stressed the importance of practical and real-world factors in the assessment by considering the industry's past experiences, local public stakeholders, investors, and media values.

Acknowledging the social dimension's challenges, particularly in data availability, uncertainty, and survey bias, is crucial (Lindfors, 2021). The data collection for social indicators can be challenging, especially for indicators like political risks/impacts and benthic seabed damages (Ibrahim et al., 2018). These challenges are exacerbated when collecting data from multiple individuals within an organization without direct collaboration with S-LCA practitioners (Tsalidis et al., 2023). Such complexities often lead to the reliance on assumptions when evaluating social impacts (Stringham and Mattson, 2021), introducing an element of uncertainty into assessments and questioning their comprehensiveness. To address the issue of data availability and improve the robustness of assessments, researchers should explore new data collection methods, such as community surveys and actively involve stakeholders, including local communities and industry experts. This involvement can enhance the accuracy of impact assessments and bridge the gap between available data and comprehensive evaluation of social and environmental impacts.

In summary, the review underscores the need for a more balanced and holistic approach to sustainability assessments in this field. A paradigm shift from a predominantly technical and economic focus to a more inclusive assessment of social and environmental aspects is warranted. Moreover, addressing the data availability issue and tackling uncertainty will enhance the robustness of assessments, contributing to a comprehensive understanding of system sustainability. Table 2 gives a summary of the most frequently used indicators in the literature. Their definition and mathematical description are given in Supplementary Information III (see Section B). Notably, brine disposal is not commonly considered in sustainability assessments, which encompass economic factors, such as disposal costs, as well as environmental and social impacts.

4.2.3. Review of decision-support tools for resource recovery systems from wastewater effluent and waste

In addition to reviewing sustainability assessments on desalination and brine treatment studies, decision-support tools for resource recovery systems from wastewater effluent and waste have been incorporated to inform the development of an assessment framework for desalination. The analysis focuses on stakeholder participation and methodological strengths and weaknesses.

While stakeholders' participation emerges as a fundamental aspect across many studies, its implementation varies. For instance, Lohman et al. (2023) and Millward-Hopkins et al. (2018) acknowledged the importance of stakeholder engagement in the development and application of sustainability assessments and decision-support tools, but lacked actual stakeholder involvement, raising questions about the validity and applicability of their findings. Conversely, Iacovidou et al. (2017) and Arushanyan, Ekener and Moberg (2017) emphasized the system thinking approach and stakeholder participation in the assessment, advocating for transparent and inclusive approaches. Ddiba et al. (2022) advocated for a context-specific approach that enables the involvement of stakeholders in diverse ways throughout the stages of the assessment process to strengthen assessment credibility.

Stakeholder participation also varies across the methodological stages and among the studies. For example, Ling, Germain and Murphy (2021) stressed the necessity of understanding the decision context and engaging stakeholders. They found that preliminary interviews can offer insights into current drivers and challenges and help identify key stakeholders. Similarly, Ladu and Morone (2021) and Ling, Germain and Murphy (2021) proposed comprehensive assessment tools that involve stakeholders in indicator selection. Ling, Germain and Murphy (2021) selected the indicators and criteria based on the insights from the preliminary interviews, while Ladu and Morone (2021) involved stakeholders through workshops, interviews and webinars for indicator selection. Similarly, Sadr et al. (2015), defined indicators based on experts' input and Ddiba et al. (2022) based on specific context relevance. Conversely, Lohman et al. (2023) defined the criteria and the indicators based on their frequency of use in previous studies.

Table 2
Summary of the most frequently used indicators in the literature.

Dimension	Indicator	Frequency	Method/Concept
Technical	Specific energy consumption	56 %	MCA, TEA, SA, EIA, Energy assessment
	Water recovery	44 %	MCA, TEA, SA, EIA, Energy assessment
	Energy consumption	33 %	MCA, TEA, SA, EIA, LCA
	Water quality	28 %	MCA, TEA, SA
Economic	OPEX	85 %	MCA, TEA, SA, Cost assessment, EIA, Energy assessment
	CAPEX	69 %	MCA, TEA, SA, Cost assessment, 3E assessment
	Freshwater produced cost	31 %	MCA, TEA, SA, 4E assessment, EIA, Energy assessment
	Unit cost	28 %	MCA, TEA, SA
Environmental	GHG emissions	62 %	MCA, TEA, SA, LCA, EIA
	GHG intensity	38 %	MCA, TEA, SA, 3E assessment, 4E assessment, LCA, EIA, Economic assessment
	Global warming	31 %	LCA
	Ecotoxicity	31 %	LCA, EIA
Social	Health and sanitation;	28 %	SA
	Acceptability	23 %	Decision support tool
	Education and training	13 %	SA
	Public safety	13 %	SA

EIA: environmental impact assessment, LCA: life cycle assessment, MCA: multi-criteria assessment, SA: sustainability assessment, TEA:techno-economic assessment.

It has also been noticed that stakeholder participation in the design of alternative scenarios (treatment chains) for evaluation varies. In particular, (Sadr et al., 2015) designed alternative scenarios based on necessity and viability, while Iacovidou et al. (2017) incorporated concepts from the circular economy and industrial symbiosis and actively engaged stakeholders in scenario communication. Similarly, Ddiba et al. (2022) developed alternative scenarios based on experts' knowledge through interviews and workshops. However, almost none of the above studies used and explained a robust methodology for the design of the alternative scenarios. Only Sadr et al. (2018) explicitly discussed the improvement of a methodology for the scenario development by exploring existing regulations, guidelines and standards for wastewater treatment and water reuse in the understudied region. Conversely, Sucu et al. (2021 and Lohman et al. (2023) use an existing knowledge database to design alternative scenarios without any feedback from relevant stakeholders, mentioning that the validity of the results depends on the information provided by the user since there is no feedback loop.

Reviews by Ddiba et al. (2023), Mannina et al. (2019), and Mustajoki and Marttunen (2017)highlighted the ongoing need for further research and improvement in decision-support tools for resource recovery plants. Specifically, Ddiba et al. (2023) emphasized the importance of understanding practitioner interaction with those tools, while Mustajoki and Marttunen (2017) stressed the importance of close collaboration with stakeholders in the multi-criteria decision analysis (MCDA) for better problem structuring and transparent inclusion of public values and concerns.

4.2.4. Key insights

The review indicates that the domain of research is relatively new, leaving room for improvements and enhancements. A key question arises: Why are existing SA methodologies underutilized in the desalination literature? Researchers often develop methodologies based on fundamental principles rather than utilizing existing frameworks, seeking greater transparency. These new approaches often focus solely on weighting and ranking methodologies, overlooking other critical steps. Without clear methodological choices, such as indicator selection and MCDA methods, results interpretation may be misleading (Pintér et al., 2012). Furthermore, the review exposes a common misuse of the term 'sustainability' in analyses, suggesting a need for greater adherence to sustainability principles. While sustainability is a popular term, its misuse can compromise the integrity of studies, undermining their credibility.

The multi-criteria decision making (MCDM) approach is favored for sustainability assessment also in the desalination field due to its ability to address the multidimensional nature of sustainability challenges. While certain studies have made progress in proposing frameworks or methodologies (e.g. (Ibrahim et al., 2018; Lior and Kim, 2018; Wang et al., 2019)), there remains a general lack of comprehensive stakeholder engagement. Relevant stakeholders' involvement in decision-making processes is often limited to the final stages in a less integrated way. This narrow engagement can lead to biased outcomes and reduce the applicability of the assessment. Furthermore, potential biases in data collection methods, such as surveys and interviews, can affect the validity of the assessments. Although social indicators provide valuable insights, they alone are not sufficient to address the complex challenges posed by desalination and resource recovery systems. The consideration of all sustainability dimensions (economic, environmental, social and/or technical) must be complemented by meaningful stakeholder participation to align resource recovery innovations with policies, markets, and societal concerns.

The reviewed studies mostly involved experts in the desalination field, neglecting the input of stakeholders with diverse backgrounds, including local community members. Additionally, data availability and quality pose challenges in obtaining reliable data, particularly for social indicators, which complicate comprehensive sustainability assessments. Culture, values, and drivers for change are rarely considered, except in works by Wreyford et al. (2020) and Rustum et al. (2020), which emphasized the significance of case-specific contextual effects in sustainability assessments, underscoring the need to consider local conditions and stakeholder insights. Conversely, studies on resource recovery from other sources (see Section 4.2.3) have demonstrated various approaches to involve stakeholders throughout the assessment process, promoting transparency and inclusivity. These studies emphasized the importance of understanding decision contexts, engaging stakeholders in indicator selection, and considering contextual relevance to enhance the credibility of the assessment.

This lack of stakeholder involvement and consideration of contextual factors highlights the need for improvements in existing works and an approach that addresses these limitations. In this regard, the implementation of VSD in the desalination field and resource recovery from seawater can significantly contribute to overcoming these shortcomings and enhancing the overall sustainability assessment process.

Based on the key insights and best practices for engaging stakeholders from the literature review, below is a list of key criteria that an SA needs to include:

- Comprehensiveness: Provide a holistic approach by integrating environmental, social, economic, and technical dimensions.
- Transparency: Provide explicit information on stakeholder participation, data collection and methodological choices, such as selecting indicators and alternative options at every stage of the process. This ensures that all decisions are open to scrutiny and accountability.
- Stakeholder participation: Promote continuous engagement and open communication with stakeholders representing diverse perspectives and interests, ensuring their inclusion in its development to provide relevant and democratic solutions. Clearly define the criteria for stakeholder selection and methods of engagement. Use participatory tools such as surveys, workshops, and focus groups to gather diverse perspectives. Identify and mitigate potential biases early by involving a diverse group of stakeholders and using reflective frameworks
- Transdisciplinary: Integrate methodologies and knowledge from different disciplines for knowledge co-production and social learning.

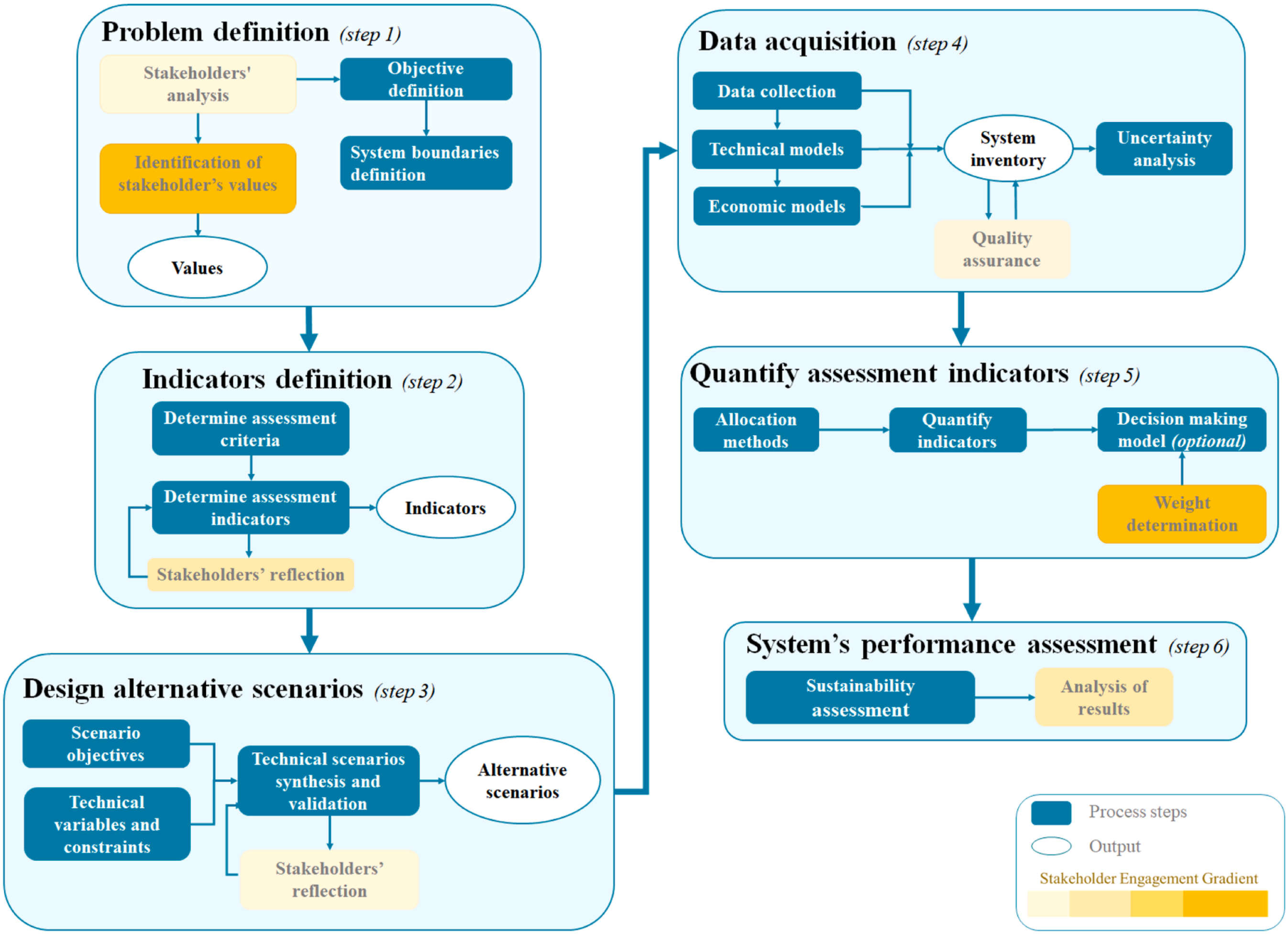


Fig. 4. Schematic representation of the proposed framework for a VSD-informed sustainability assessment of desalination and brine management. The Stakeholder Engagement Gradient illustrates varying degrees of stakeholder involvement across different steps, ranging from light gold-yellow indicating low involvement to dark gold-yellow indicating high involvement.

4.3. Synthesis: a proposed framework to assess integrated desalination and brine treatment systems

Building upon the theoretical background outlined in Section 2 and insights from the literature reviews in Sections 4.2.2 and 4.2.3, an assessment framework was developed. The framework consists of six steps: (1) Problem definition, (2) Assessment indicators definition, (3) Design of alternative scenarios, (4) Data acquisition, (5) Assessment indicators quantification, and (6) Performance analysis. Fig. 4 illustrates the proposed framework in a block flow diagram, incorporating the stakeholder engagement gradient to denote the degree of participation at each step. This framework provides various levels of investigation by considering insights from experts and literature. The following subsections give a detailed description of the individual steps.

4.3.1. Problem definition

The proposed framework is developed to be applicable to different case studies; thus, it is essential to describe and understand the case study in the early stage of the assessment. For this, the framework proposes establishing stakeholder engagement followed by a participatory definition of the problem statement.

Stakeholder analysis and engagement: The involvement of a diverse range of stakeholders, including researchers, policymakers, engineers, and affected communities, is crucial. Grouping these stakeholders by their interests and potential impact ensures that all relevant perspectives are integrated into the assessment process (Bryson, 2004; Reed et al., 2009). Note that not only technical experts or stakeholders that benefit from the integrated system should be considered in the analysis, but also stakeholders that might be indirectly affected or even lose from it need to be part of the group (Voinov et al., 2016). For example, in an integrated seawater desalination and resource recovery project, stakeholders might include local communities affected by brine disposal, companies involved in resource recovery like the salt industry and technology developers/suppliers, and environmental organizations overseeing the environmental impacts. A list of potential stakeholder groups is given in Supplementary Information III (see Section C), while Bryson (2004) discusses in detail the stakeholder identification and analysis techniques.

Active involvement: Once the stakeholder analysis is conducted, the next step is to actively involve stakeholders in the assessment process. While the proposed participatory approach aims to involve stakeholders at various stages of the assessment process, the level of participation of each stakeholder can vary. Factors such as power, capacity, interest, and the ability to engage must be considered when determining their participation (see example in Supplementary Information III, Section C). The level of participation ranges from informing them to collaborating with them to initiate the process. The most intense participation occurs when local stakeholders initiate the process, perform the analyses, and are involved in the decision-making processes. They also have ownership of the data inputs and final products. There is no optimal level of participation. The degree of participation depends on the specific study (Voinov et al., 2016). It is important to ensure that all stakeholders, regardless of their interests or potential gains or losses, are given equal consideration in the participatory process, promoting democratization, ownership, and transparency. Participation should start early and continue throughout the stakeholder analysis to enhance process effectiveness.

Each step clarifies when and how stakeholders should be involved and at what level of engagement, ensuring a transparent and collaborative process. For example, in the problem definition step, stakeholder participation and engagement are particularly crucial, as early involvement generates interest and ensures that community needs and values are accurately reflected. The level of participation should be high, requiring substantial input and feedback from stakeholders, while the degree of engagement should involve a wide variety of stakeholders to gather diverse perspectives. This early and continuous involvement ensures that the assessment is grounded in a comprehensive understanding of the stakeholders' concerns and objectives.

Addressing biases: Identifying and addressing potential biases early in the assessment process is crucial. Involving a diverse group of stakeholders will not only provide multiple perspectives but also reduce individual bias. Critical Systems Heuristics offers a reflective framework and tools, such as *"boundary questions"* to explore system biases (Ulrich and Reynolds, 2010).

Transparency: is a critical aspect at all participatory stages, from the selection and invitation of stakeholders to the development of engagement activities and the analysis of outcomes. Transparency in stakeholder engagement means openly communicating the criteria for stakeholder selection, the methods of engagement, and how stakeholder inputs are integrated into the assessment. This ensures that decisions regarding stakeholder participation are made openly, addressing questions of who is included and on what grounds, taking into account the motivations and intentions of both stakeholders and practitioners/ facilitators (Voinov et al., 2016). Participatory tools, including surveys, workshops, focus groups, brainstorming, group facilitation, SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis, and mind mapping or a combination of tools facilitate stakeholder engagement (Hamilton et al., 2015; Voinov et al., 2016).

Problem statement definition: Described and analysed the problem statement and information, such as location, available energy sources, market availability, and constraints. Furthermore, to identify and analyse the main sustainability issues considering the sociotechnical context around the case study, a thorough review of relevant literature, policy documents, and stakeholder inputs should be conducted (Azapagic and Perdan, 2005a). This process can involve evaluating the environmental, economic, and social impacts and exploring potential trade-offs between different sustainability dimensions. It is crucial to transparently communicate any simplifications made during this process to ensure the study's robustness and clarity.

Additionally, understanding the current challenges and drivers is an essential opportunity to engage with key stakeholders. Including social-cultural aspects in the description of the case study will not only add value to the assessment (Sala, 2020) but also help in the design of alternative scenarios (see Section 4.3.3). This can be achieved by conducting workshops, interviews, or surveys with stakeholders (local communities, experts, researchers) to gather insights on the socio-cultural context, values, and preferences that should be considered during the assessment process. The identification of stakeholders' values is a critical step in the proposed framework, and it has to be carried out in the early stage of the assessment.

System boundaries and objectives: Define the objectives of the assessment and set system boundaries. The system boundary outlines the scope of the system being assessed, specifying what is included and excluded in the analysis. For instance, in a sustainability assessment of an integrated seawater desalination and brine treatment plant, the system boundary might include the intake of seawater, the desalination process itself, brine treatment processes for resource recovery, the output of fresh water and other recovered materials, and the disposal of brine. This represents a cradle-to-gate system boundary, focusing on the operation phase of the system and excluding equipment manufacturing and downstream activities like the distribution of desalinated water to consumers. Recognizing biases related to system boundaries and key assumptions is inherent, as these are defined by the practitioners/ facilitators and can influence the assessment outcomes. For example, excluding the distribution network might overlook significant environmental impacts from transportation and emissions. Transparency about biases and their implications is essential for managing their impact.

Decision-making tools: The proposed framework can be applied either for soft decision-making tools, which focus on decision support and require minimal information, or hard decision-making tools, which utilize mathematical programming techniques and require extensive information. However, the choice between soft and hard decision-making tools needs to be determined in this step. The choice between soft and hard MCDA depends on several factors, such as the objective, complexity of the problem, availability of data, and resource availability (Mendoza and Martins, 2006) (see example in Supplementary Information III, Section C).

To sum up, the following questions need to be answered:

- Who are the stakeholders, and what is their level of participation?
- What is the goal of the assessment?
- What are stakeholders' values?
- What are the current drivers and challenges?
- What is the approach of the decision-making tool (soft or hard) and the level of comprehensiveness?
- What are the system boundaries (geographical, time) of the assessment?

For a visual representation of the problem definition process, tools, and considerations, refer to Figure C.1 (see Supplementary Information III, Section C).

4.3.2. *Indicators definition*

This section describes how sustainability issues and the identified values from the previous step (see problem definition) are translated into performance indicators. The connection between the identified values and the selected indicators ensures that the assessment is relevant and focused on the case study. This work proposes the definition of the performance indicators before the development of alternative scenarios and data acquisition. This is essential to ensure a consistent and transparent approach, minimizing the potential influence of participants' interests on the assessment process. By selecting indicators at this stage, the methodology remains robust and unbiased throughout its execution. After designing alternative scenarios, the indicators can always be updated to ensure their relevance and representativeness.

The indicators can be selected on the basis of a literature review (see the developed database in Supplementary Information I). This database serves as a solid foundation, offering a comprehensive list of indicators categorized by their relevance and application in desalination and brine treatment studies. For instance, in a case study focusing on the technical performance of resource recovery, users can refer to technical indicators such as water recovery efficiency and specific energy consumption for a product from the database. While this database is a starting point, it is crucial to remain open to other performance indicators from the literature and adjust them individually to each case study, the identified values, and the objective of the assessment. The goal is not to lead directly to common indicators but to offer guidance on overall indicator system design and analysis (Pintér et al., 2012).

A large number of indicators would increase the complexity of the assessment. For this reason, a clear-cut approach is needed for selecting the individual indicators (Singh et al., 2012), and some of them are excluded. The most relevant indicators are selected to comprehensively assess the systems and provide valuable insights, following guidelines. A theory-driven approach is used, and data is only one of the many aspects considered (Gasparatos, El-Haram and Horner, 2008). In particular, the selection of performance indicators is primarily based on four critical criteria:

1) Relevance to stakeholders' values: Indicators should directly reflect stakeholders' values and address the problem statement and the systems under study (applicability and practicability).
2) Measurability and data availability: The selected indicators should be measurable, and data should be readily available to quantify them.
3) Comprehensiveness: The indicators should collectively provide a comprehensive view of the system's performance.
4) Transparency: Indicator selection and measurement should be transparent and easily understandable (Foxon et al., 2002; Azapagic and Perdan, 2005a). This means providing stakeholders with detailed information about how indicators were chosen, how they align with stakeholder values, and the process for evaluating their relevance.

Note that the selected indicators should not allow compensation. This means that a gain in one aspect (e.g., economic benefits) should not be used to justify a loss in another (e.g., environmental degradation). Furthermore, a well-balanced set of indicators might better represent the diverse value orientations of the stakeholders (Gasparatos and Scolobig, 2012). In a participatory approach, as in our study, effective communication with the stakeholders and guiding decision-makers is essential. To enhance communication and evaluate the result better, the indicators have to be understandable, straightforward (using clear and plain language), and present information objectively (Pintér et al., 2012). Although "user friendliness" is one of the main advantages of reductionism (Gasparatos, El-Haram and Horner, 2008), for this framework, we can accept partial reductionism for the benefit of effective communication.

Finally, it's essential to share both the selected indicators and the followed procedure with relevant stakeholders to ensure transparency and collaboration in the final selection of the indicators. The level of participation should be substantial, with stakeholders providing critical feedback and recommendations on the selection process, and the degree of engagement should be high, involving a variety of stakeholders to gather diverse opinions. For instance, during workshops or surveys, stakeholders could identify alternative indicators or suggest modifications to existing ones that better align with their concerns. This feedback could lead to adjustments in the selection of indicators to ensure they reflect the stakeholders' values more accurately. Below is an example of a primary selection of indicators based on given values.

For a practical example, the relationship between values, objectives, and indicators is that values determine the objective employed to evaluate alternative scenarios, while the indicators are the parameters that measure the performance of those scenarios in alignment with the objective. Consider evaluating a resource recovery configuration (integrated seawater desalination and brine treatment system) in terms of water and energy security. Specifically, the value of water security might be evaluated by measuring the system's water production quantity, which reflects how effectively the system recovers water from seawater. This enables an assessment of the overall resource recovery from seawater and ensures a comprehensive evaluation of water security. This contribution/impact is assigned to the technical dimension. Similarly, 'energy security' can be assessed by monitoring both electrical and thermal energy consumption, alongside the integration of renewable energy sources. By quantifying these indicators, we can assess the overall impact of the configuration on water and energy security, ensuring that the system aligns with stakeholder values and objectives.

4.3.3. *Design of alternative scenarios*

The review of existing assessment studies in the literature reveals a lack of robust reasoning behind the selection of alternatives or the design of alternative scenarios (systems) (Lindfors, 2021) (see Micari, Moser, et al., 2020; Ronquim et al., 2020). Choosing what alternatives to include can become very challenging and complicated, especially when technologies are integrated into a system. While conventional MCA methodologies begin by selecting alternatives after or within the scope definition. (Lindfors et al., 2019; Lindfors, 2021), in this work, the design of alternative scenarios comes after the definition of the indicators. This adjustment is made to ensure transparency in the assessment process and prevent stakeholders' interests or preferences from influencing indicator selection. By selecting indicators without prior knowledge of the alternatives, we ensure that stakeholders' interests or preferences do not affect the choice of indicators. This approach allows for a more objective and unbiased assessment, as the selected indicators are independent of the specific scenarios and are solely based on their relevance to the sustainability dimensions and identified values. Consequently, the evaluation of alternatives remains consistent and fair, focusing on their actual contribution to sustainability objectives rather than being influenced by any predetermined preferences or expectations.

The development of technical scenarios is based on the identified values from Step 1 (see Section 4.3.1) and active participation in the identification of solutions. These technical scenarios present various ways of combining technologies to achieve the objectives(s) while considering stakeholders' values. They aim to gain valuable insights into important variables around the technology and how different technical configurations address specific societal aspects. Transparency in this phase involves clearly documenting the process and rationale behind the selection of any technical alternatives (process configuration). This includes being aware of potential biases for specific technologies or products clearly documenting these choices helps ensure unbiased evaluation and builds stakeholder trust.

For a practical example, in a recent review of resource recovery from brines and other wastewater (Palmeros Parada et al., 2022), energy and GHG emissions, cost and affordability impacts, and societal perceptions on the ownership of water and recovered resources were discussed as prominent issues that can bring forth tensions around resource recovery from desalination brines. These issues are distinct from the identified values in the sense that they represent the broader concerns and challenges related to the sustainability of the case study. While their analysis was not specific for a given geographical context or case study, it allows us to derive general objectives in response to sustainability and societal concerns around resource recovery innovations for seawater desalination:

- Minimize energy use and GHG emissions: ensuring that resource recovery processes are energy-efficient and have a low carbon footprint.
- Minimize additional costs to existing water supply services: ensuring that the resource recovery does not significantly increase the cost of water for consumers.
- Maximize the recovery of resources, especially water and scarce or critical resources: focusing on extracting valuable materials from brine, such as minerals and high-quality water.

However, it is impossible to satisfy all objectives at once. Thus, technical scenarios can serve to evaluate and bring trade-offs to discussion. Considering the objectives and the associated challenges mentioned above, three principles for developing scenarios are:

- Water recovery focus: Prioritizing the recovery of fresh water from brine.
- Resource recovery focus: Emphasizing the extraction of valuable minerals and other resources.
- Minimum liquid discharge: Aiming to minimize the volume of brine discharge and not resource recovery.

These principles are proposed as a starting point for developing detailed scenarios for specific case studies, structured around three main technical scenario variables: (1) process and technology, (2) product and by-products, and (3) raw materials and utilities (Parada et al., 2017). Additionally, insights and lessons learned from the literature and technology experts are used to design the technical scenarios.

Stakeholders should be engaged in providing feedback on the design of the technical scenarios to ensure the incorporation of diverse perspectives and technical knowledge and to avoid biases. The level of participation should be moderate, with stakeholders offering critical insights and recommendations. The degree of engagement should be low, involving a small, focused group of stakeholders with technical expertise to refine the scenarios and ensure they align with the broader sustainability objectives.

4.3.4. *Data acquisition*

One of the most critical steps in the assessment frameworks is data acquisition because it is directly related to the accuracy, reliability, and quality of the results. The effectiveness of the assessment framework depends on securing access to accurate and high-quality data from different sources (Singh et al., 2012; Nika et al., 2020). From the literature review, it was found that one of the main limitations of previous works is the availability of data (Jia et al., 2019; Saleh and Mezher, 2021). For these reasons, when reliable data from stakeholders are not available, the use of technical models consisting mainly of mass and energy balances is recommended as an alternative.

For instance, a GitHub repository offers technical process and economic models for integrated seawater desalination and brine treatment technologies for resource recovery (https://github.com/rodoulak/Desalination-and-Brine-Treatment-Simulation-.git). These models provide a valuable resource for generating data when direct stakeholder inputs are limited. They offer pre-built models for simulating various desalination and brine treatment scenarios, which can be tailored to fit the specific parameters and indicators identified in Section 4.3.2.

In general, more complex models can provide more data, but the complexity does not necessarily correlate with usefulness or accuracy (Li et al., 2022). The selection of the methods, models, tools, or algorithms depends on the assessment's objective. In light of the challenges associated with data availability, particularly in early-stage assessments, the use of technical and economic models emerges as a valuable approach to ensure the availability of sufficient and high-quality data for quantifying technical, economic, and environmental indicators.

It is important to note that the framework does not rely on specific tools like LCA. Instead, it suggests using simpler methods for data generation. Surveys, interviews, and literature reviews are required to determine the social indicators (Wasserman and Faust, 1994). These methods play a crucial role in the data collection process, providing valuable information and ensuring consideration of different perspectives. High-quality survey and workshop methodologies are essential for robust data collection.

It is important to recognize that biases can arise in data acquisition due to assumptions made during data collection and model selection. For example, excluding certain data sources or relying on specific models can introduce bias, impacting the results. To manage these biases, use a broad range of data sources to balance perspectives and clearly document and communicate all assumptions made.

The participation of stakeholders is important to ensure the availability of high-quality data and manage bias. Engaging stakeholders actively in this step not only enhances data reliability but also fosters transparency, trust, and collaboration among stakeholders, and their feedback helps identify and correct biases in the data. Transparency in this phase means clearly documenting the sources of data, the methods of collection, and any assumptions made during this process. Stakeholders play a dual role in providing and validating data. In particular, stakeholders have a dual role in this process: they provide data and validate it. Their involvement in giving data—through sources such as local knowledge, expert insights, and empirical evidence—ensures the inclusion of diverse perspectives and real-world relevance. Additionally, stakeholders help to validate the data by reviewing and confirming its accuracy and applicability. Stakeholders should receive both performance data during stakeholder engagement and the final results of the analysis (Akadiri and Olomolaiye, 2012).

In case of data gaps, methods like mean substitution or correlation results can be applied. However, it is necessary to assess the suitable method that can produce reliable results (Singh et al., 2012). After the data collection, uncertainty analysis has to be done to increase the reliability, accuracy, and validity of the data. The various sources of data or some of the input data to the model can affect the uncertainty of the model (Nika et al., 2020). Thus, it is vital to analyse and quantify the uncertainty of the data (Baustert et al., 2018). This can be done through various methods, such as sensitivity analysis or Monte Carlo simulation

(Li et al., 2022). The choice of method depends on the specific assessment and the data being analysed. The next step is the integration of the technical, economic, and environmental models. The number of models to be combined should be decided carefully. The higher the number of coupled models and tools, the higher the complexity of the integrated model (Nika et al., 2020).

Overall, engaging stakeholders in the data acquisition process not only provides access to crucial information but also helps to build trust and increase transparency. Stakeholder participation helps to validate the data, address data gaps, and improve the overall quality of the assessment results. Note that the degree of participation (number of stakeholders involved) is low.

4.3.5. *Performance analysis: quantify assessment indicators and alternative scenarios analysis*

In this step, the interpretation of the results is carried out to provide decision-makers with a comprehensive evaluation of the alternative scenarios and required information for decision-making. The approach in this step must be adjusted based on the nature of the MCDA being employed (soft or hard), see problem definition (Section 4.3.1) and Supplementary Information III (Section C). Particularly in hard MCDA, once the selected indicators are determined using the data acquired in Step 4 (Section 4.3.4), their values must be scaled into dimensionless values (normalized) for analysis and comparison. This is necessary because the various performance indicators have different physical dimensions (units) (Saad, Nazzal and Basil M. Darras, 2019). Additionally, the performance analysis in hard MCDA includes more steps, such as selecting the MCDM method for weight determination, aggregation, alternatives ranking, and sensitivity analysis. Conversely, in soft MCA, normalization is not necessary. The performance analysis in soft MCDA focuses on interpreting the results without the need to scale the indicator values to provide structured knowledge and support decision-making.

Nowadays, it is well-accepted that there is no “best” MCDM method (Diaz-Balteiro, González-Pachón and Romero, 2017). Instead, the selection of suitable MCDA methods for ranking and weighting depends on the characteristics of the problem, such as the data, the scope of the study, and the number of indicators (Singh et al., 2012; Diaz-Balteiro, González-Pachón and Romero, 2017). Determining weights aims to assign relative importance to indicators, reflecting their significance in decision-making. Weighting dimensions and indicators have been a critical issue in the sustainability literature (Turkson et al., 2020). In general, MCDA methods have been classified as (i) utility function (AHP, Multi-Attribute Utility Theory (MAUT), Simple Additive Weighting (SAW)), (ii) outranking relation (ELECTRE, PROMETHEE) and (iii) sets of decision rules (Cinelli, Coles and Kirwan, 2014). Wen, Lindfors and Liu (2023) and Kumar and Kumar (2017) give an overview of MCDM methods, their description, strengths, and weaknesses. Note that for strong sustainability, only outranking methods can be selected due to the limited or abolished compensation among/within sustainability dimensions. This means that improvements in one dimension (e.g., economic) cannot offset or *“compensate”* for declines in another (e.g., environmental). In contrast, methods such as MAUT and AHP are more aligned with a weak sustainability perspective, with criteria trade-offs as the norm (Munda, 2008; Cinelli, Coles and Kirwan, 2014). Detailed definitions of strong and weak sustainability are provided in Supplementary Information III (see Section A).

In the field of desalination, AHP emerged as the most frequently utilized method in the reviewed studies to handle complexity, uncertainty and consistency, followed by Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) (see Table 1). However, it was observed that many studies did not provide explicit justification for selecting a particular MCA method. There were exceptions, such as the work by Lior and Kim (2018) that briefly explained the rationale for choosing and (Ghassemi and Danesh, 2013), who explained that fuzzy-AHP and TOPSIS were selected to address uncertainty and sensible attributes with simplified programming methods. New MCDA methods, such as the Best-Worst method (BMW), developed by Rezaei (2015), has been extensively applied in other fields (Rezaei, Wang and Tavasszy, 2015; Salamirad et al., 2023; Wen, Lindfors and Liu, 2023) but has not yet been explored in the context of desalination.

Stakeholder groups often have varying preferences when evaluating options. Traditional methods of evaluation aggregate these preferences into a single weight or index. However, aggregation can be problematic when dealing with a large number of stakeholders, conflicting opinions or extreme opinions. In such cases, the average weight may not represent everyone’s opinion, leading to a loss of valuable information. This can ultimately reduce the effectiveness of the decision-making process (Garmendia and Gamboa, 2012; Mustajoki and Marttunen, 2017). In sustainability assessment studies, it can be more beneficial to focus on understanding the decision-making process and differences in stakeholders’ opinions rather than arriving at a final ranking for alternatives. While there may not be a definitive answer to sustainability performance, a participatory approach that involves stakeholders can help them learn and better understand the situation.

Transparency in performance analysis involves documenting and communicating every methodological choice, rationale, and assumption made during this phase. This includes explaining why certain MCDA methods are chosen, how weights are determined, and how indicators are normalized or not. This transparency is further ensured by presenting analysis results and interpretations to stakeholders, as mentioned also in data acquisition. This approach allows stakeholders to understand the decision-making process, fostering accountability and trust in the assessment outcomes.

Stakeholder involvement is crucial in decision-making for informed choices that reflect community needs and values. The active participation of diverse stakeholders ensures a comprehensive evaluation that considers diverse perspectives, values, and stakeholder needs.

5. Impact, limitations, and future work

A critical review of the state of SA for desalination and brine treatment systems found that there is no existing sustainability framework for integrated systems in the literature. To address this gap, this study proposed an SA framework integrating methods from various fields, including VSD, to assess the sustainability performance of integrated desalination and brine treatment systems for resource recovery.

Incorporating VSD helped consider social challenges and enhance existing methodologies. By incorporating stakeholders’ values and value tensions into the assessment process, we encourage a context-specific selection of indicators that resonates with the preferences and priorities of those affected by the decisions. This integration allows for a more inclusive and participatory approach, democratizing the decision-making process and promoting transparency and credibility.

The developed indicator database (see Supplementary Information I) is a valuable resource for selecting performance indicators tailored to desalination and brine treatment case studies. It significantly contributes to the research community by providing a structured, accessible repository of indicators, enhancing SAs through transparent and adaptable selection. Offering a wide range of technical, economic, environmental, and social indicators, the database supports comprehensive and relevant evaluations, advancing the field of SA. The proposed methodology can guide the user in identifying improved opportunities through the development and evaluation of alternative technical scenarios where social and stakeholders’ values are incorporated. This broadened step is missing in existing frameworks in the literature. Overall, the integration of key elements from VSD and other fields, enabled the development of a robust SA framework, filling the research gap with a comprehensive and transparent assessment methodology that considers the interconnections between economic, environmental, social, and technical aspects. It involves stakeholders throughout the assessment process and incorporating their values, ensuring relevance to their concerns and ambitions.

The developed sustainability assessment framework is designed to be applicable to a range of users. Potential users include researchers conducting academic studies on desalination and resource recovery, government agencies involved in policy-making and regulation of water treatment technologies, plant owners or operators looking to enhance the sustainability of their operations, and investors or consultants evaluating future developments in the desalination sector.

The framework can be applied beyond seawater desalination to various technological domains. By adapting indicators to suit specific contexts, it offers a consistent and robust assessment methodology across different fields, such as wastewater treatment, renewable energy systems, and industrial resource recovery. This systematic approach facilitates informed decision-making and promotes sustainable practices.

Bias in SA is unavoidable, stemming from the decision-makers' choices regarding system boundaries and assumptions. To manage bias, this framework recommends several strategies: (1) explicitly identify and document potential biases from the start, (2) involve a diverse range of stakeholders to balance perspectives, (3) ensure transparency in all methodological choices, (4) use reflective tools like Critical Systems Heuristics to examine and refine assumptions, and (5) regularly update the assessment based on feedback and new insights. These steps aim to enhance the robustness and credibility of assessments.

While this study recognizes the significance of stakeholder involvement and proposes a participatory approach, it is crucial not only to engage stakeholders in an existing project or process but also to include them in its development. However, effective stakeholder engagement throughout the assessment requires substantial time, resources, and coordination. Stakeholders' availability, influenced by their existing tasks and commitments, can limit their engagement. To address this, it is essential to communicate the benefits of the assessment framework (Ling, Germain and Murphy, 2021).

Moreover, reducing conflicts and building trust among stakeholders is vital for moving towards a shared vision (Hamilton et al., 2015). Educating stakeholders, including researchers and decision-makers, about the benefits of collaboration can facilitate meaningful engagement. Future research should focus on developing effective strategies and methodologies to enhance participation. Finally, exploring case studies and real-world applications of the framework in different contexts can provide valuable insights into the practical implementation of stakeholder engagement and the associated benefits and limitations.

Future work should implement the proposed framework, including mathematical models for formulating, calculating, and analysing sustainability performance and integrating different analytical tools to develop a multi-sectoral system without increasing the complexity.

6. Conclusions

The literature review identified critical shortcomings in current sustainability assessments for seawater desalination and brine treatment systems. These assessments notably lack a comprehensive approach and neglect social aspects and stakeholder involvement. To address these deficiencies, we proposed a novel Sustainability Assessment (SA) framework that integrates participatory multi-criteria analysis and value-sensitive design into the decision-making process. This approach advances SA by recognizing the importance of incorporating social dimensions through stakeholders' values, enhancing the framework's robustness and aligning decision-making with stakeholders' concerns and ambitions.

The proposed framework offers a comprehensive tool for evaluating the sustainability of integrated seawater desalination and resource recovery systems. By incorporating detailed stakeholder analysis and practical examples, it guides users/decision-makers in identifying improved opportunities through the development and evaluation of alternative technical scenarios, considering social and stakeholders' values, a vital step missing in current literature. Additionally, the developed indicator database, readily available for researchers and practitioners, serves as a starting point for selecting indicators to support the implementation of the proposed framework.

The proposed SA framework offers a comprehensive and transparent assessment methodology ready to be employed in real-world situations. Future work should include implementing the proposed framework in real-world situations to prove its effectiveness and address the limitations and improvements that need to be made.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT to improve the clarity and readability of this text. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

CRediT authorship contribution statement

Rodoula Ktori: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Mar Palmeros Parada:** Writing – review & editing. **Marcos Rodriguez-Pascual:** Writing – review & editing. **Mark C.M. van Loosdrecht:** Writing – review & editing, Supervision, Conceptualization. **Dimitrios Xevgenos:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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.

Data availability

No data was used for the research described in the article.

Acknowledgments

This work has been funded by EU within the WATER MINING project (Next generation water smart management systems: large scale demonstrations for a circular economy and society) – Horizon 2020 program, Grant Agreementno. 869474.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107954.

References

Abdulbaki, D., et al., 2020. Multi-criteria decision making for the selection of best practice seawater desalination technologies'. Frontiers in Water-Energy-Nexus—Nature-Based Solutions, Advanced Technologies and Best Practices for Environmental Sustainability, pp. 489–492.

Afgan, N.H., Darwish, M., Carvalho, M.G., 1999. Sustainability assessment of desalination plants for water production. Desalination 124 (1–3), 19–31. https://doi.org/10.1016/S0011-9164(99)00085-5.

Akadiri, P.O., Olomolaiye, P.O., 2012. Development of sustainable assessment criteria for building materials selection. Eng. Constr. Arch. Manage. 19 (6), 666–687. https://doi.org/10.1108/09699981211277568.

Arushanyan, Y., Ekener, E., Moberg, Å., 2017. Sustainability assessment framework for scenarios – SAFS. Environ. Impact Assess. Rev. 63, 23–34. https://doi.org/10.1016/j.eiar.2016.11.001.

Azapagic, A., Perdan, S., 2005a. An integrated sustainability decision-support framework Part I : problem structuring. Int. J. Sustain. Develop. World Ecol. 4509. https://doi.org/10.1080/13504500509469622.

Azapagic, A., Perdan, S., 2005b. An integrated sustainability decision-support framework Part II : problem analysis. Int. J. Sustain. Develop. World Ecol. 4509. https://doi.org/10.1080/13504500509469623.

Aziz, N.I.H.A., Hanafiah, M.M., 2021. Application of life cycle assessment for desalination: progress, challenges and future directions. Environ. Pollut. 268, 115948. https://doi.org/10.1016/J.ENVPOL.2020.115948.

Balfaqih, H., et al., 2017. Environmental and economic performance assessment of desalination supply chain. Desalination 406, 2–9. https://doi.org/10.1016/J.DESAL.2016.08.004.

Baustert, P., et al., 2018. Uncertainty analysis in integrated environmental models for ecosystem service assessments: frameworks, challenges and gaps. Ecosyst. Serv. 33, 110–123. https://doi.org/10.1016/J.ECOSER.2018.08.007.

Bello, A.S., et al., 2021. An overview of brine management : emerging desalination technologies, life cycle assessment, and metal recovery methodologies. J. Environ. Manage. 288 (March), 112358. https://doi.org/10.1016/j.jenvman.2021.112358.

Bick, A., Oron, G., 2005. Post-treatment design of seawater reverse osmosis plants: boron removal technology selection for potable water production and environmental control. Desalination 178 (1–3), 233–246. https://doi.org/10.1016/J.DESAL.2005.01.001.

Bond, A., Morrison-Saunders, A., Pope, J., 2012. Sustainability assessment: the state of the art. Impact Assess. Project Appraisal 30 (1), 53–62. https://doi.org/10.1080/14615517.2012.661974.

Bryson, J.M., 2004. What to do when stakeholders matter: stakeholder Identificatixon and analysis techniques. Public Manage. Rev. 6 (1), 21–53. https://doi.org/10.1080/14719030410001675722.

Chen, Q., et al., 2021. A zero liquid discharge system integrating multi-effect distillation and evaporative crystallization for desalination brine treatment. Desalination 502, 114928. https://doi.org/10.1016/J.DESAL.2020.114928.

Cinelli, M., Coles, S.R., Kirwan, K., 2014. Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. Ecol. Indic. 46, 138–148. https://doi.org/10.1016/j.ecolind.2014.06.011.

Cipolletta, G., et al., 2021. Brine treatment technologies towards minimum/zero liquid discharge and resource recovery: state of the art and techno-economic assessment. J. Environ. Manage. 300 (August), 113681. https://doi.org/10.1016/j.jenvman.2021.113681.

Commission, E. (2020) *A new circular economy action plan. For a cleaner and more competitive Europe.* Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN.

Davis, J., Nathan, L.P., 2016. Handbook of ethics, values, and technological design. Handbook of Ethics, Values, and Technological Design. Springer. https://doi.org/10.1007/978-94-007-6970-0_3.

Ddiba, D., et al., 2022. Sustainability assessment of increased circularity of urban organic waste streams. Sustain. Prod. Consump. 34, 114–129. https://doi.org/10.1016/j.spc.2022.08.030.

Ddiba, D., et al., 2023. A review of how decision support tools address resource recovery in sanitation systems. J. Environ. Manage. 342 (March). https://doi.org/10.1016/j.jenvman.2023.118365.

Diaz-Balteiro, L., González-Pachón, J., Romero, C., 2017. Measuring systems sustainability with multi-criteria methods: a critical review. Eur. J. Oper. Res. 258 (2), 607–616. https://doi.org/10.1016/j.ejor.2016.08.075.

Elsaid, K., et al., 2020. Environmental impact of desalination technologies: a review. Sci. Total Environ. 748, 141528. https://doi.org/10.1016/J.SCITOTENV.2020.141528.

Foxon, T.J., et al., 2002. Sustainability criteria for decision support in the UK water industry. J. Environ. Plann. Manage. 45 (2), 285–301. https://doi.org/10.1080/09640560220116341.

Friedman, B., Hendry, D.G., Borning, A., 2017. A survey of value sensitive design methods. Found. Trends Hum. Comp. Inter. 11 (23), 63–125. https://doi.org/10.1561/1100000015.

Friedman, B., Kahn, P.H., Borning, A., 2015. Value sensitive design and information systems. Hum. Comput. Inter. Manage. Inform. Syst. Found. 348–372. https://doi.org/10.4324/9781315703619-27.

Gargalo, C.L., et al., 2016. A framework for techno-economic & environmental sustainability analysis by risk assessment for conceptual process evaluation. Biochem. Eng. J. 116, 146–156. https://doi.org/10.1016/j.bej.2016.06.007.

Garmendia, E., Gamboa, G., 2012. Weighting social preferences in participatory multi-criteria evaluations: a case study on sustainable natural resource management. Ecol. Econ. 84, 110–120. https://doi.org/10.1016/j.ecolecon.2012.09.004.

Gasparatos, A., El-Haram, M., Horner, M., 2008. A critical review of reductionist approaches for assessing the progress towards sustainability. Environ. Impact Assess. Rev. 28 (4–5), 286–311. https://doi.org/10.1016/j.eiar.2007.09.002.

Gasparatos, A., Scolobig, A., 2012. Choosing the most appropriate sustainability assessment tool. Ecol. Econ. 80, 1–7. https://doi.org/10.1016/j.ecolecon.2012.05.005.

Ghassemi, S.A., Danesh, S., 2013. A hybrid fuzzy multi-criteria decision making approach for desalination process selection. Desalination 313, 44–50. https://doi.org/10.1016/J.DESAL.2012.12.008.

Hajeeh, M., Al-Othman, A., 2005. Application of the analytical hierarchy process in the selection of desalination plants. Desalination 174 (1), 97–108. https://doi.org/10.1016/J.DESAL.2004.09.005.

Hamilton, S.H., et al., 2015. Integrated assessment and modelling: overview and synthesis ofsalient dimensions. Environm. Modell. Softw. 64, 215–229. https://doi.org/10.1016/j.envsoft.2014.12.005.

Herva, M., Roca, E., 2013. Review of combined approaches and multi-criteria analysis for corporate environmental evaluation. J. Clean. Prod. 39, 355–371. https://doi.org/10.1016/j.jclepro.2012.07.058.

van den Hoven, J., Vermaas, P.E., van de Poel, I., 2015. Handbook of ethics, values, and technological design: sources, theory, values and application domains. Handbook of Ethics, Values, and Technological Design: Sources, Theory, Values and Application Domains, pp. 1–871. https://doi.org/10.1007/978-94-007-6970-0.

Iacovidou, E., et al., 2017. A pathway to circular economy: developing a conceptual framework for complex value assessment of resources recovered from waste. J. Clean. Prod. 168, 1279–1288. https://doi.org/10.1016/j.jclepro.2017.09.002.

Ibrahim, Y., et al., 2018. An integrated framework for sustainability assessment of seawater desalination. Desalination 447, 1–17. https://doi.org/10.1016/J.DESAL.2018.08.019.

Jia, X., et al., 2019. Analyzing the energy consumption, GHG emission, and cost of seawater desalination in China. Energies 12 (463). https://doi.org/10.3390/en12030463.

Kehrein, P., et al., 2020. The SPPD-WRF framework : a novel and holistic methodology for strategical planning and process design of water resource factories. Sustainability.

Kumar, A., et al., 2017. A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. Renew. Sustain. Energy Rev. 69 (June 2016), 596–609. https://doi.org/10.1016/j.rser.2016.11.191.

Ladu, L., Morone, P.P., 2021. Holistic approach in the evaluation of the sustainability of bio-based products: an integrated assessment tool. Sustain. Prod. Consump. 28, 911–924. https://doi.org/10.1016/j.spc.2021.07.006.

Lee, K., Jepson, W., 2021. Environmental impact of desalination: a systematic review of Life Cycle Assessment. Desalination 509, 115066. https://doi.org/10.1016/J.DESAL.2021.115066.

Li, Y., et al., 2022. Quantitative sustainable design (QSD) for the prioritization of research, development, and deployment of technologies: a tutorial and review. Environ. Sci. Water Res. Technology 2439–2465. https://doi.org/10.1039/d2ew00431c.

Lindfors, A., et al., 2019. Assessing the potential, performance and feasibility of urban solutions : methodological considerations and learnings from biogas solutions. Sustainability 11.

Lindfors, A., 2021. Assessing sustainability with multi-criteria methods: a methodologically focused literature review. Environ. Sustain. Indic. 12 (September), 100149. https://doi.org/10.1016/j.indic.2021.100149.

Ling, J., Germain, E., Murphy, R., 2021. Designing a sustainability assessment framework for selecting sustainable wastewater treatment technologies in corporate asset decisions. Sustainability 13 (3831).

Lior, N., 2017. Sustainability as the quantitative norm for water desalination impacts. Desalination 401, 99–111. https://doi.org/10.1016/J.DESAL.2016.08.008.

Lior, N., Kim, D., 2018. Quantitative sustainability analysis of water desalination – a didactic example for reverse osmosis. Desalination 431, 157–170. https://doi.org/10.1016/J.DESAL.2017.12.061.

Lohman, H.A.C., et al., 2023. DMsan: a multi-criteria decision analysis framework and package to characterize contextualized sustainability of sanitation and resource recovery technologies. ACS Environ. Au 3 (3), 179–192. https://doi.org/10.1021/acsenvironau.2c00067.

Loutatidou, S., et al., 2017. Introduction: what is sustainable desalination? Desalination Sustainability: A Technical, Socioeconomic, and Environmental Approach, pp. 1–30. https://doi.org/10.1016/B978-0-12-809791-5.00001-8.

Mannina, G., et al., 2019. Decision support systems (DSS) for wastewater treatment plants – a review of the state of the art. Bioresour. Technol. 290 (May). https://doi.org/10.1016/j.biortech.2019.121814.

Mansour, F., et al., 2018. Screening and cost assessment strategies for end-of-pipe zero liquid discharge systems. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2018.01.064.

Mavukkandy, M.O., et al., 2019. Brine management in desalination industry: from waste to resources generation. Desalination 472 (November), 114187. https://doi.org/10.1016/j.desal.2019.114187.

Mendoza, G.A., Martins, H., 2006. Multi-criteria decision analysis in natural resource management: a critical review of methods and new modelling paradigms. For. Ecol. Manage. 230 (1–3), 1–22. https://doi.org/10.1016/j.foreco.2006.03.023.

Meneses, M., Pasqualino, J.C., Raquel, C., 2010. Alternatives for reducing the environmental impact of the main residue from a desalination plant. J. Ind. Ecol. 14 (3). https://doi.org/10.1111/j.1530-9290.2010.00225.x.

Mezher, T., et al., 2011. Techno-economic assessment and environmental impacts of desalination technologies. Desalination 266 (1–3), 263–273. https://doi.org/10.1016/J.DESAL.2010.08.035.

Micari, M., Cipollina, A., et al., 2020. Techno-economic analysis of integrated processes for the treatment and valorisation of neutral coal mine effluents. J. Clean. Prod. 270, 122472. https://doi.org/10.1016/J.JCLEPRO.2020.122472.

Micari, M., Moser, M., et al., 2020. Towards the implementation of circular economy in the water softening industry: a technical, economic and environmental analysis. J. Clean. Prod. 255, 120291. https://doi.org/10.1016/j.jclepro.2020.120291.

Miller, J.K., et al., 2007. Value tensions in design: the value sensitive design, development, and appropriation of a corporation's groupware system. In: GROUP'07 - Proceedings of the 2007 International ACM Conference on Supporting Group Work, pp. 281–290. https://doi.org/10.1145/1316624.1316668.

Millward-Hopkins, J., et al., 2018. Fully integrated modelling for sustainability assessment of resource recovery from waste. Sci. Total Environ. 612, 613–624. https://doi.org/10.1016/j.scitotenv.2017.08.211.

Mohsen, M.S., Al-Jayyousi, O.R., 1999. Brackish water desalination: an alternative for water supply enhancement in Jordan. Desalination 124 (1–3), 163–174. https://doi.org/10.1016/S0011-9164(99)00101-0.

Morgante, C., et al., 2022. Valorisation of SWRO brines in a remote island through a circular approach: techno-economic analysis and perspectives. Desalination 542, 116005. https://doi.org/10.1016/J.DESAL.2022.116005.

Morgante, C., et al., 2024. Pioneering minimum liquid discharge desalination : a pilot study in Lampedusa Island. Desalination 581.

Munda, G., 2006. Social multi-criteria evaluation for urban sustainability policies. Land Use Policy 23 (1), 86–94. https://doi.org/10.1016/J.LANDUSEPOL.2004.08.012.

Munda, G., 2008. Social multi-criteria evaluation for a sustainable economy. Soc. Multi-Crit. Eval. Sustain. Econ. https://doi.org/10.1007/978-3-540-73703-2.

Mustajoki, J., Marttunen, M., 2017. Comparison of multi-criteria decision analytical software for supporting environmental planning processes. Environ. Modell. Softw. 93, 78–91. https://doi.org/10.1016/j.envsoft.2017.02.026.

Nayar, K.G., et al., 2019. Cost and energy needs of RO-ED-crystallizer systems for zero brine discharge seawater desalination. Desalination 457, 115–132. https://doi.org/10.1016/J.DESAL.2019.01.015.

Ness, B., et al., 2007. Categorising tools for sustainability assessment. Ecol. Econ. 60 (3), 498–508. https://doi.org/10.1016/j.ecolecon.2006.07.023.

Nika, C.E., et al., 2020. Water cycle and circular economy: developing a circularity assessment framework for complex water systems. Water Res. 187, 116423. https://doi.org/10.1016/J.WATRES.2020.116423.

Ogunbiyi, O., et al., 2021. Sustainable brine management from the perspectives of water, energy and mineral recovery: a comprehensive review. Desalination 513, 115055. https://doi.org/10.1016/J.DESAL.2021.115055.

Oosterlaken, I., 2014. Applying value sensitive design (VSD) to wind turbines and wind parks: an exploration. Sci. Eng. Ethics 21 (2), 359–379. https://doi.org/10.1007/s11948-014-9536-x.

Palmeros Parada, M., et al., 2020. Integrating value considerations in the decision making for the design of biorefineries. Sci. Eng. Ethics 26 (6), 2927–2955. https://doi.org/10.1007/s11948-020-00251-z.

Palmeros Parada, M., et al., 2022. Societal values, tensions and uncertainties in resource recovery from wastewaters. J. Environ. Manage. 319, 115759. https://doi.org/10.1016/j.jenvman.2022.115759.

Palmeros Parada, M., et al., 2023. Resource recovery from desalination, the case of small islands. Resour. Conserv. Recycl. 199 (October). https://doi.org/10.1016/j.resconrec.2023.107287.

Palmeros Parada, M., Osseweijer, P., Posada Duque, J.A, 2017. Sustainable biorefineries, an analysis of practices for incorporating sustainability in biorefinery design. Ind. Crops Prod. 106, 105–123. https://doi.org/10.1016/J.INDCROP.2016.08.052.

Panagopoulos, A., 2021a. Beneficiation of saline effluents from seawater desalination plants: fostering the zero liquid discharge (ZLD) approach - a techno-economic evaluation. J. Environ. Chem. Eng. 9 (4), 105338. https://doi.org/10.1016/J.JECE.2021.105338.

Panagopoulos, A., 2021b. Energetic, economic and environmental assessment of zero liquid discharge (ZLD) brackish water and seawater desalination systems. Energy Conver. Manage. 235, 113957. https://doi.org/10.1016/J.ENCONMAN.2021.113957.

Panagopoulos, A., 2021c. Techno-economic assessment of minimal liquid discharge (MLD) treatment systems for saline wastewater (brine) management and treatment. Process Safety Environ. Prot. 146, 656–669. https://doi.org/10.1016/J.PSEP.2020.12.007.

Panagopoulos, A., 2022. Techno-economic assessment of zero liquid discharge (ZLD) systems for sustainable treatment, minimization and valorization of seawater brine. J. Environ. Manage. 306, 114488. https://doi.org/10.1016/J.JENVMAN.2022.114488.

Panagopoulos, A., Haralambous, K.J., Loizidou, M., 2019. Desalination brine disposal methods and treatment technologies - a review. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2019.07.351.

Papapetrou, M., et al., 2017. Assessment of methodologies and data used to calculate desalination costs. Desalination 419 (May), 8–19. https://doi.org/10.1016/j.desal.2017.05.038.

Parada, M.P., et al., 2017. Setting the design space of biorefineries through sustainability values, a practical approach. Biofuels Bioprod. Biorefin. (12), 29–44. https://doi.org/10.1002/bbb.

Pintér, L., et al., 2012. Bellagio STAMP : principles for sustainability assessment and measurement. Ecol. Indic. 17, 20–28. https://doi.org/10.1016/j.ecolind.2011.07.001.

Raluy, G., Serra, L., Uche, J., 2006. Life cycle assessment of MSF, MED and RO desalination technologies. Energy 31 (13), 2361–2372. https://doi.org/10.1016/J.ENERGY.2006.02.005.

Reed, M.S., et al., 2009. Who's in and why? A typology of stakeholder analysis methods for natural resource management. J. Environ. Manage. 90 (5), 1933–1949. https://doi.org/10.1016/j.jenvman.2009.01.001.

Ren, J., et al., 2020. Sustainability assessment framework for the prioritization of urban sewage treatment technologies. Waste-to-Energy 153–176. https://doi.org/10.1016/B978-0-12-816394-8.00006-9.

de Reuver, M., et al., 2020. Digital platforms and responsible innovation: expanding value sensitive design to overcome ontological uncertainty. Ethics Inf. Technol. 22 (3), 257–267. https://doi.org/10.1007/s10676-020-09537-z.

Rezaei, J., 2015. Best-worst multi-criteria decision-making method. Omega (Westport) 53, 49–57.

Rezaei, J., Wang, J., Tavasszy, L., 2015. Linking supplier development to supplier segmentation using Best Worst Method. Expert Syst. Appl. 42 (23), 9152–9164. https://doi.org/10.1016/j.eswa.2015.07.073.

Ronquim, F.M., et al., 2020. Eco-efficiency analysis of desalination by precipitation integrated with reverse osmosis for zero liquid discharge in oil refineries. J. Clean. Prod. 250, 119547. https://doi.org/10.1016/J.JCLEPRO.2019.119547.

Rustum, R., et al., 2020. Sustainability ranking of desalination plants using mamdani fuzzy logic inference systems. Sustainability 12 (631). https://doi.org/10.3390/su12020631.

Saad, M.H., Nazzal, M.A., Darras, Basil M., 2019. A general framework for sustainability assessment of manufacturing processes. Ecol. Indic. 97, 211–224. https://doi.org/10.3390/su12124957.

Sadr, S.M.K., et al., 2015. A group decision-making tool for the application of membrane technologies in different water reuse scenarios. J. Environ. Manage. 156, 97–108. https://doi.org/10.1016/j.jenvman.2015.02.047.

Sadr, S.M.K., et al., 2018. A multi expert decision support tool for the evaluation of advanced wastewater treatment trains: a novel approach to improve urban sustainability. Environ. Sci. Policy 90 (August), 1–10. https://doi.org/10.1016/j.envsci.2018.09.006.

Sala, S., 2020. *Triple Bottom line, Sustainability and Sustainability assessment, an overview, Biofuels for a More Sustainable Future.* Elsevier Inc. https://doi.org/10.1016/B978-0-12-815581-3.00003-8.

Sala, S., Ciuffo, B., Nijkamp, P., 2015. A systemic framework for sustainability assessment. Ecol. Econ. 119, 314–325. https://doi.org/10.1016/J.ECOLECON.2015.09.015.

Sala, S., Farioli, F., Zamagni, A., 2013. Progress in sustainability science: lessons learnt from current methodologies for sustainability assessment: part 1. Int. J. Life Cycle Assess. 18 (9), 1653–1672. https://doi.org/10.1007/s11367-012-0508-6.

Salamirad, A., et al., 2023. Wastewater treatment technology selection using a hybrid multicriteria decision-making method. Int. Trans. Oper. Res. 30 (3), 1479–1504. https://doi.org/10.1111/itor.12979.

Saleh, L., Mezher, T., 2021. Techno-economic analysis of sustainability and externality costs of water desalination production. Renew. Sustain. Energy Rev. 150, 111465. https://doi.org/10.1016/J.RSER.2021.111465.

Shende, A.D. et al. (2021) 'Optimal selection of "zero liquid discharge" (ZLD) system using "analytical hierarchy process" (AHP) and "grey relational analysis" (GRA)', 23, pp. 8506–8523. doi: 10.1007/s10668-020-00979-5.

Singh, R.K., et al., 2012. An overview of sustainability assessment methodologies. Ecol. Indic. 15 (1), 281–299. https://doi.org/10.1016/J.ECOLIND.2011.01.007.

Sola, I., Sáez, C.A., Sánchez-Lizaso, J.L., 2021. Evaluating environmental and socio-economic requirements for improving desalination development. J. Clean. Prod. 324. https://doi.org/10.1016/j.jclepro.2021.129296.

Stringham, B.J., Mattson, C.A., 2021. Design of remote data collection devices for social impact indicators of products in developing countries. Develop. Eng. 6 (January). https://doi.org/10.1016/j.deveng.2021.100062.

Sucu, S., et al., 2021. A conceptual framework for a multi-criteria decision support tool to select technologies for resource recovery from urban wastewater. J. Environ. Manage. 300 (August). https://doi.org/10.1016/j.jenvman.2021.113608.

Tsalidis, G.A., et al., 2023. Social life cycle assessment of a desalination and resource recovery plant on a remote island: analysis of generic and site-specific perspectives. Sustain. Prod. Consump. 37, 412–423. https://doi.org/10.1016/J.SPC.2023.03.017.

Turkson, C., et al., 2020. Sustainability assessment of energy production: a critical review of methods, measures and issues. J. Environ. Manage. 264 (April). https://doi.org/10.1016/j.jenvman.2020.110464.

Ulrich, W., Reynolds, M., 2010. Systems approaches to managing change: a practical guide. Systems Approaches to Managing Change: A Practical Guide. Springer, London, pp. 243–292. https://doi.org/10.1007/978-1-84882-809-4.

UN (2001) *Indicators of sustainable development: guidelines and methodologies.*

Voinov, A., et al., 2016. Modelling with stakeholders - next generation. Environ. Modell. Softw. 77, 196–220. https://doi.org/10.1016/j.envsoft.2015.11.016.

Wang, Z., et al., 2019. Sustainable desalination process selection: decision support framework under hybrid information. Desalination 465, 44–57. https://doi.org/10.1016/J.DESAL.2019.04.022.

Wasserman, S., Faust, K., 1994. Social Network analysis : Methods and Applications. Cambridge University Press, Cambridge, UK. LK. https://tudelft.on.worldcat.org/oclc/840275872.

Wen, Q., Lindfors, A., Liu, Y., 2023. How should you heat your home in the green energy transition? A scenario-based multi-criteria decision-making approach. J. Clean. Prod. 421 (August). https://doi.org/10.1016/j.jclepro.2023.138398.

Wreyford, J.M., et al., 2020. Modelling framework for desalination treatment train comparison applied to brackish water sources. Desalination 494, 114632. https://doi.org/10.1016/J.DESAL.2020.114632.

Xevgenos, D., 2016. Creating Value Out of Seawater Desalination Brines Through the Recovery of Water and salts, Using Renewable Energy Sources. National Technical University of Athens. https://doi.org/10.12681/eadd/37648. Available at.

Xevgenos, D. et al. (2018) 'Integrated Brine Management: a circular economy approach', in Smart Water Grids: A Cyber-Physical Systems Approach. 1st edn.

Xevgenos, D. et al. (2021) 'Aspects of environmental impacts of seawater desalination: cyprus as a case study', 211, pp. 15–30. doi: 10.5004/dwt.2021.26916.

Xevgenos, D., et al., 2024. The concept of circular water value and its role in the design and implementation of circular desalination projects. The case of coal mines in Poland. Desalination 579 (September 2023). https://doi.org/10.1016/j.desal.2024.117501.

Zhou, J., Chang, V.W.C., Fane, A.G., 2013. An improved life cycle impact assessment (LCIA) approach for assessing aquatic eco-toxic impact of brine disposal from seawater desalination plants. Desalination 308, 233–241. https://doi.org/10.1016/J.DESAL.2012.07.039.