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Evaluation of brine management strategies from the perspective of the sustainable development goals: Application in the canary islands

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HIGHLIGHTS

- Sustainable brine management of seawater desalination plants
- Environmental management strategies from the perspective of the Sustainable Development Goals
- Brine management monitoring indicators

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ABSTRACT

The desalination of seawater is presented as the solution to cover the demand for water in a future scenario of the climate crisis. Nevertheless, desalination also has environmental impacts, with the discharge of brine into the sea being the most worrying. For this reason, many projects seek technologies that allow desalination discharge to be transformed into a more sustainable activity.

However, evaluating the sustainability of brine management strategies is a complex task that has not been developed until now. The article analyzes brine management from a holistic point of view and proposes establishing strategies based on sustainability objectives that may, in turn, be compatible with the United Nations Sustainable Development Goals. As a result, a framework of 7 Sustainable Brine Management Goals, 11 targets and 18 monitoring indicators is proposed. In addition, a practical case has been developed to evaluate with indicators the scope of these goals in the Canary Islands, Spain.

1. Introduction

The demand for drinking water has increased significantly and will continue to grow and with it the production of desalinated water, which today is around 142 M cubic meters per day [1]. At the same time, periods of drought will become more severe in some regions due to climate change; thus, seawater desalination is considered to be an effective strategy to secure water supply in the future.

However, desalination processes produce a by-product called 'brine' that is characterized by its high salinity. Hypersalinity and chemicals present in brine make its discharge into the sea complicated, posing a threat to the most sensitive marine communities and ecosystems [2]. Therefore, sustainable brine management has become the main concern for the desalination industry [3].

In the last decade research on the detrimental effect of brine on marine species and ecosystems due to its hypersaline characteristic has grown considerably. For instance, a study has shown that brine negatively affects benthic heterotrophic bacteria in the emissary area [4]. It has also been studied that the effect of brine with the presence of chemicals, such as polyphosphonate-based antifosphonate, harms coral species due to multiple stressors [5]. Further research has demonstrated that the effects of high salinity combined with additives increase the speed and the symptoms of stress in *Posidonia australis* seagrasses compared to treatments without additives [6].

Many of the chemicals present in brine can be treated or replaced by others with less impact on the environment. For example, improving the pretreatment of seawater can reduce the use of polyphosphonate-based antifosphonate. Another option is the subsequent treatment of brine, such as coagulation by chemical precipitation, oxidation and biological processes [7], or replacement with green antifouling agents or biodegradable compounds that do not contain phosphorus [8].

On the other hand, most chemicals used in desalination processes are

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difficult to trace in the marine environment. For this, it is necessary to base the evaluation of the impacts on representative marine organisms [9]. Also, the use of bioindicators is recommended because they can discriminate between the impacts of different activities that may overlap in the same area and could produce early warning signals for the application of corrective measures [10].

To control the good state of the waters, regular environmental monitoring is carried out. In addition, some initiatives aim to improve measurement techniques through early warning systems by introducing seabed probes (sensors) [11]. Nevertheless, in some cases, one can find monitoring plans in which it is required to measure irrelevant descriptors for brine discharge [12], and in other cases, the frequency of sampling could be considered insufficient.

A useful tool to assess the impact of brine on desalination technologies can be the Life Cycle Assessment (LCA). However, this tool requires a large amount of detailed data and information from feasible and reliable sources, so the impact assessment of brine disposal is not properly integrated into many LCA studies on desalination [13]. In addition, because of these deficiencies associated with LCA, some authors have underestimated the ecotoxic effects of brine removal. For this reason, other researchers have proposed an improved LCA approach called the “group-by-group” approach to assessing the impact of more complex and variable seawater desalination concentrates [14].

Despite these advances, it is still necessary to explore the application of this methodology considering a holistic point of view, as well as to pay more attention to the social and economic aspects of desalination [15]. Besides, there is still a need to expand research on the impact of brine discharge on a greater number of species and ecosystems, such as studies of benthic meiofauna, as well as eukaryotic algae [4], or on the effects of seawater reverses osmosis (SWRO) plants desalination in hard corals considering changes in temperature and presence of coagulants [5]. Also, aspects such as the drag effect of discharge jets or the cumulative environmental impact on biomonitors should continue to be studied [9,16].

The characteristics of the brine, the location, and the chosen technical solution determine the potential impact of the discharge. A traditional strategy to minimize the impact of brine is its pre-dilution, with purified water, seawater, or cooling water from power plants. In the latter case, the predilution with cooling water has a dual purpose as cooling water dilutes salinity and minimizes temperature increase [9].

One of the most widely used solutions to minimize the impact of discharges is the use of underwater outfalls with a diffuser section. Several studies consider submarine diffuser systems to be the best technology available, due to their high dilution capacity [4,5]. However, new technologies are being proposed to increase the dilution capacity in the discharge system; some examples are venturi-type diffusers [17] and confined plunging jets, which are increasingly being studied [18]. For the design of the discharge through submarine diffusers software that simulates the behaviour of the brine is used to predict the impact on the marine environment. Some of the most popular software are CORMIX, Visual Plumes, and brIHne. However, the process of mixing the brine jet with the marine environment entails complex processes, e.g., advective processes associated with waves, which these tools are not able to model. In such cases, the use of more complex Computational Fluid Dynamics (CFD) software with greater computational capacity is necessary [19].

A prediction model will be more reliable when validated or compared with measurement data, including discharge measurements of real operating systems, so prediction tools still have a wide field for improvement [20]. Therefore, it is necessary to carry out additional studies on the different discharge systems focusing on quantitative descriptions, including the dilution rate and the synergistic effects between different types of discharges [21].

Another major concern is the high energy use that desalination processes require [22]. Brine management is directly related to the energy consumption of the desalination plant. A significant example is a need for extra pumping for pre-dilution of the discharge or the use of energy exchange equipment widely used in reverse osmosis plants that allow energy savings. One way to reduce the impact of energy use is the development of innovative techniques capable of capturing CO_2 using brine, reducing greenhouse gas emissions [23]. Another way to reduce the CO_2 derived from energy consumption is to incorporate renewable energy, this is key to the environmental sustainability of desalination [20]. The combination of Renewable Energy (RR.EE.) in desalination processes still requires more research and demonstration projects that ensure longer-term performance [24]. Blue energy, also known as osmotic energy or salinity gradient energy, is renewable energy which uses the salinity gradient for power generation and is attracting growing attention, technologies like *Pressure Retarded Osmosis* (PRO) and *Reversible Electrodialysis* (RED) they can obtain clean energy using brine and other lower salinity effluent. *Forward Osmosis* (FO) is another technology that takes advantage of the saline gradient between two flows. Which can concentrate a liquid effluent, thus reducing the volume of waste to be treated and facilitating its transport. The application of FO promises to be an option to reduce the energy consumption of liquid concentration processes, used in various industries, such as the dairy and livestock industry, fruit juices and drinks, the brewing industry, chemical and pharmaceutical industries, mining, textile and even for drying algae. However, its application with brine from SWRO plants presents problems such as internal membrane polarization (ICP) and the need for previous treatments [25].

Finally, the new challenge to improve the sustainability of brine management is its transformation from waste to resource and its integration into a circular economy. To achieve that, one option is to reduce brine to high purity solid salts to sell the salts and dispose of solid waste [2]. Also, previous evaluations have proposed, as a viable solution, the implementation of a chlor-alkali industry annexed to the desalination reverse osmosis plants [26]. Another solution to give a new value to brine is its direct use in other industries such as fish and halophytes production [1]. One of the most recent proposals is the recovery of metals present in the brine, such as uranium, lithium, cesium, rubidium, indium, gallium, potassium, or germanium. From an environmental point of view, the recovery of metals could avoid the impact produced by mines or other extraction technologies [27]. However, this approach entails complex and expensive processes, and further investigations are yet to be implemented on a pilot scale [3].

It is a fact that the growth and development of the desalination industry should consider and implement new technologies and strategies to promote sustainability [8]. In the regions that are committed to the massive implementation of desalination, there is widespread concern about the efficiency of brine management tools and sustainable land management. The Sustainable Development Goals (SDGs) framework introduced by the United Nations (UN), composed of 17 global goals and 169 targets, provides an opportunity to critically evaluate current models of development and production and to favour the application of sustainable models. So the article aims to integrate brine management strategies into the fulfilment of sustainable development goals. To date, a comprehensive analysis of how brine management for water desalination plants can contribute to the progress of the SDGs has not been carried out.

However, the Development Goals Framework may in some cases be ambiguous or it may not be easy to recognize a direct relationship with them. For this reason, in many cases, it is difficult and complex to tabulate participation in the fulfilment of the SDGs, especially when assessing the contribution of specific activities, projects or emerging technologies. In addition to this, the particularities of each region, the different ecosystems, the breadth of the desalination industry and the wide variety of technologies and actors present in this sector, it does difficult to establish common management criteria that allow evaluating and comparing progress in sustainable brine management.

Studies on brine management strategies have so far focused on the classification of available technologies and their analysis of advantages and disadvantages, such as strategies based on Zero Liquid Discharge (ZLD) technologies, brine reuse or landfill methods [28]. However, the fact is that the available technologies are diverse and it is complex to evaluate and compare the degree of sustainability between them, or in some cases, it is only possible to evaluate certain characteristics.

To bridge this gap, the article defines brine management strategies with a new approach based on a framework of goals and targets that provides the industry with a roadmap aligned with the SDGs. This proposal is made up of seven strategies or goals and ten targets, ranging from the most traditional management strategies, such as reducing the volume of brine discharged and its environmental monitoring at sea, to the most innovative ones such as the recovery of brine or its energy use with blue energy technologies. In addition, to evaluate the fulfilment of the objectives, a set of seventeen indicators is proposed based on the bibliography and the experiences and proposals of the different actors of the water sector, operators, administration, scientific community, etc.…

The methodology is applied in a practical case developed for seawater desalination plants in the Canary Islands (Spain). The analysis of the Canary island region was selected based on the fact the extensive experience in desalination, the high density of desalination plants, and the willingness of local companies and public institutions to invest in the desalination sector. The region has a desalinated water production capacity of over 660,000 m^3/day and approximately 319 desalination plants [29] playing a crucial role due to high dependence on unconventional water resources. The Canary has marine biodiversity of great value, species such as *Cymodocea nodosa* are characteristic of these waters and have high sensitivity to salinity variations that brine discharges produce. For all these reasons, there is widespread interest in considering new sustainable development strategies.

This case study is the first study to define and analyze brine management strategies from the perspective of sustainable development goals, providing the baseline scenario for the study region.

2. Methodology

Assessing how to brine management activities can move us closer to or further away from the sustainability goals is a complex task that has not been studied before. To carry out this assessment, we conducted a state-of-the-art study on techniques and strategies for sustainable brine management in SWRO plants and a detailed analysis of the SDG framework, looking at the specific targets, indicators, structure and tools in place.

However, brine management strategies are currently classified according to the technologies used, but given the variety of technological solutions, management policies and social and environmental contexts, this way of classifying management models cause a fundamental limitation when trying to link management strategies to the SDGs.

Thus, the article proposes a new approach for the classification of brine management strategies that allows them to be linked to the SDGs. This proposal consists of defining management strategies in terms of goals that we have called Brine Management Goals (BMG). In this way we have two objective frameworks structured similarly, being able to develop a relationship matrix between them.

The framework proposes a new holistic point of view of brine management, moving from a plant operation level to a territorial management level, it is considered that brine management is not only the responsibility of the manager of a desalination plant but also includes all the actors that add value to brine management and its impacts.

The structure of the SDGs was taken as a reference for the framework proposal. At the first level are the global objectives or strategies. These strategies have been selected based on the previous study on the state of the art in brine management. In the second level of the framework, the objectives were raised, these specify in greater detail the paths to follow. This approach was recommended by the Global Reporting Initiative (GRI), the United Nations Global Compact and the World Business Council for Sustainable Development (WBCSD) in the SDG Compass guide to help companies align their strategies with the achievement of the SDGs through its strategic objectives, but never before had it been adapted to the objectives of an industry (Table 1).

Finally, to assess the progress of the SDGs through brine management strategies, a set of indicators was proposed to quantify the evolution in compliance with the BMG. The definition of these metrics, for each of the established objectives, is necessary to be able to quantify the approach or regression of the proposed goals (Fig. 1).

2.1. Methodology for the quantification of the indicators

In this section, the methodological processes applied are specified. Since various sources of information have been consulted, it has been necessary in some cases to imitate the searches, homogenise the data or establish hypotheses in the calculation of the indicators.

2.1.1. Indicators for BMG-1: impact of the discharge

The indicators proposed for the monitoring of the BMG-1 are mainly related to the design and operation of the desalination plants, these

Table 1
Proposed sustainable brine management framework and indicators.

Goals	Targets	Proposed indicators
1. Minimize the impact of the discharge on the marine environment	1.1. Reduce the volume of brine discharged into the sea.	1.1.1 Volume of brine discharged into the sea per year. 1.1.2 Salinity of brine discharge.
	1.2. Reduce the pollutant load discharged into the sea	1.2.1. Percentage of brine discharge points into the sea with prior dilution. 1.2.2. Submarine outfalls with diffuser section.
	1.3. Eliminate harmful compounds from the discharged brine.	1.3.1 Use of green chemicals.
2. Regulation and control of discharge	2.1. Guarantee regulations that ensure the good state of the quality of waters and ecosystems.	2.1.1. Specific regulations for brine discharges at the regional level. 2.1.2 Authorized discharges
	2.2. Guarantee the correct control and environmental monitoring of brine discharges.	2.2.1. Percentage of environmental monitoring plans
3.Reducing CO_2	3.1. Increase the efficiency of the desalination plant 3.2. Use of renewable energies	3.1.1. Specific energy consumption of the plant. 3.2.1. Contribution of RR. EE. at the desalination plant
4.Blue energy	4.1 Implementation for technologies to use natural osmotic pressure with desalination brine	4.1.1. Number of pilot scale installations 4.1.2. Number of installations on an industrial scale
5. Circular economy	5.1. Valorization of brine, achieve its transformation from waste to resource.	5.1.1. Identification of uses, elements and applicability. 5.1.2 Volume of compounds on the market per year. 5.1.3. Management of by-products generated.
6. Innovation	6.1 Promote innovation, synergy with other industries and Public-Private collaboration	6.1.1. Number of patents related to desalination.
7.Applied research	7.1 Expand knowledge about desalination and the effect brine has on marine ecosystems.	7.1.1. Number of theses. 7.1.2. Number of academic publications.

Own elaboration.

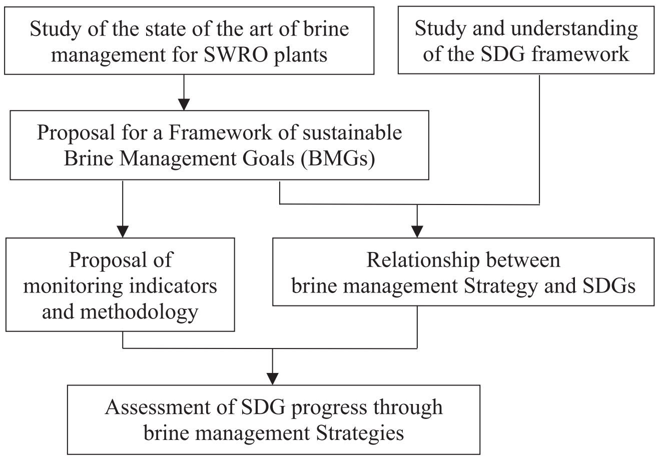

Fig. 1. Process diagram of the proposed methodology.

allow us to represent the quantity and quality of the brine discharged for subsequent evaluation.

- Indicator 1.1.1. Annual volume of brine generated by seawater desalination plants.

The volume of brine has been obtained by adding the volumes of the official list of desalination plants, both public and private. Annual volume units have been expressed in hm^3/year. In cases of having only the average daily flow or the average flow per hour, the annual volume has been estimated considering a continuous production of 24 h 7 days a week. In cases where the exact discharge value was not available, the annual volume of water produced and the average recovery factor was taken for the estimation of the annual brine volume.

- Indicator 1.1.2. Salinity of brine discharge.

The discharge salinity has been estimated by knowing the average salinity value in the receiving medium and the average recovery factor of the desalination plants.

$$S_e = \frac{S_s}{(1 - R)} \tag{1}$$

S_e = Salinity of effluent
S_s = Salinity of seawater
R = Recovery factor

In turn, the average recovery factor has been estimated from annual the volume data of desalinated water and discharged brine production.

$$R = \frac{V_p}{(V_p + V_e)} \cdot 100 \tag{2}$$

V_p = Volumen production
V_e = Volumen effluent
R = Recovery factor

- Indicator 1.2.1. Discharge of brine into the sea with prior dilution or joint discharge techniques.

The indicator has been expressed as a percentage (%), to calculate it has been counted the points of discharges registered that contain brine effluent and classified depending on the nature of the effluents: discharges containing only brine, discharges with brine and wastewater, brine and cooling water or brine and seawater.

- Indicator 1.2.2. Discharged into the sea with underwater pipeline with diffuser section.

The indicator, expressed as a percentage (%), has been calculated after accounting for the points of discharges containing brine effluent collected in the official census. The discharges have been classified according to their method of discharge: point of discharge in a cliff, stone beach, discharge with submarine outfall, submarine outfall with diffusers sector and open channel.

- Indicator 1.3.1: Green chemicals used in desalination processes.

Conventional chemicals are used in most installations for pretreatment or membrane cleaning and maintenance processes, such as coagulants-flocculants, antiscalants, antioxidants, etc. The application of chemical processes in the treatments affects the quality of the brine and its polluting capacity, so they should be eliminated or replaced by green chemicals that do not add toxicity. It is proposed to represent in percentage the volume of green chemicals used concerning conventional chemicals.

2.1.2. Indicators for BMG-2: regulation & control

The indicators proposed for the monitoring of the BMG-2 include the metrics to quantify the level of control or monitoring that public authorities have over the conditions of brine discharges into the sea.

- Indicator 2.1.1. Specific regulations for brine discharges at the regional level.

We searched the legislation and official guides or recommendations about the discharge of brine at the national and regional levels applicable to the case of study.

- Indicator 2.1.2. Percentage of authorized discharges.

The brine discharge points have been classified according to their legal status, differentiating three categories, 'authorized' when they meet the technical, environmental, and administrative criteria established by the competent authorities, and 'not authorized-in process' or 'not authorized' otherwise. The result of the indicator, authorized discharges, was expressed as a percentage.

- Indicator 2.2.1. Environmental Monitoring Plan (EMP).

The selected indicator indicates the percentage of brine discharges into the sea that has a monitoring plan in place in the discharge area. The EMPs carry out the monitoring activities, and their contents and parameters to be analyzed may vary depending on the circumstances of each case. Generically, EMPs contain indicators of the characteristics of the effluent and receiving waters, as well as indicators of the quality of sediments and organisms present in the vicinity of the discharge point, for example, it is usual to establish a maximum of 10 % in the increase in salinity with respect to the value of the receiving medium.

2.1.3. Indicators for BMG-3: reducing CO_2

The brine management activities influence the energy consumption of a desalination plant, assuming one more impact to consider and that must be evaluated and monitored.

- Indicator 3.1.1. Energy consumption associated with brine management.

The indicator collects the consumption in kWh/m^3 considering the total of the treatments associated with brine management, such as the consumption of the pumps for the pre-dilution of the concentrate.

- Indicator 3.2.1. Contribution of RR.EE. at the desalination plants.

The total energy consumed by desalination in the Canary Islands was estimated at 1184 GWh/year by multiplying the production of desalinated water, which is 242.16 Hm^3 [29], by the average specific energy consumption (SEC) in the Canary Islands of 4.89 kWh/m^3 [30]. On the other hand, the annual energy supplied by renewable sources was estimated by accounting for the capacity of the renewable energy infrastructure associated with desalination plants and a production of 2800 equivalent hours per year in wind farms and 3300 equivalent hours per year for photovoltaic facilities.

2.1.4. Indicators for BMG-4: blue energy

Trying to obtain energy using the osmotic pressure generated by facing two flows of different salt concentrations is not new, but some technical difficulties have not yet been overcome to efficiently use desalination brine on an industrial scale. However, *Pressure Retarded Osmosis* (PRO) and *reversible electrodialysis* (RED) technologies are presented as future technologies for the generation of electricity through the saline gradient. In addition to the above, *Forward osmosis (FO)* technologies have also been considered in this objective since they have an energy advantage by taking advantage of the natural osmotic pressure in the dilution/dehydration processes.

- Indicator 4.1.1. Number of pilot-scale installations.

We have searched for pilot-scale projects with Blue Energy technologies installed in the study region.

- Indicator 4.1.2. Number of desalination plants with Blue Energy technologies on an industrial scale.

We have searched for existing industrial-scale Blue Energy technologies operating in the study region.

2.1.5. Indicators for BMG-5: circular economy

The valorization of brine is one of the management challenges that are of most interest to the industry. Research is currently underway to valorise the brine most efficient and cost-effective way as possible. This paper proposes some indicators to evaluate the implementation of the circular economy in desalination.

- Indicator 5.1.1. Identification of uses, elements and applicability.

The paper analyzes the studies and projects on brine valorization carried out in the study region, identifying the feasibility of uses and exploitation of elements.

- Indicator 5.1.2. Volume of compounds from brine valued and marketed.

The study tries to quantify the volume of brine used for a circular economy purpose.

- Indicator 5.1.3. Management of by-products generated.

Today there is no standardized methodology for the management of by-products generated in the recovery processes or the management of solid waste produced by ZLD technologies.

2.1.6. Indicators for BMG-6: innovation

Innovation can be a very broad concept, in our study the number of patents has been proposed since it has been considered a good indicator to quantify investment in technologies or the emergence of new ideas. We understand that the trend is to develop more sustainable solutions to existing ones and it is interesting to consider them as part of the progress in desalination and brine management.

- Indicator 6.1.1. Number of patents related to new developments and technologies in desalination.

The patents have been searched in the database of the national patent office, using the keywords: brine and desalination. The patents considered in the indicator are those whose applicants had their main headquarters in the region of study. The results have been classified, according to the main function of the invention, into four topics: process, energy, membrane or environment. At the same time, the results have been classified depending on the legal nature of the applicant in the private company, public institution or University.

2.1.7. Indicators for BMG-7: applied research

Finally, the paper proposes a holistic point of view of brine management, not only oriented to the management of the plant, in this way other stakeholders, such as universities, are involved and responsible for the management of the brine. Deepening and advancing knowledge is essential to progress in understanding impacts and proposing new approaches and solutions.

- Indicator 7.1.1. Number of theses directly related to desalination and its sustainability.

This indicator reflects the number of theses defended at the University of the study region, they have been classified according to their main theme in the topics: process energy, membrane or environment.

- Indicator 7.1.2. Number of articles referring to desalination or its impacts.

The articles considered in this indicator are those whose first author represents a University or Research Center belonging to the region of study.

2.2. Classification of indicators by their level of maturity

In the last step, a maturity analysis was carried out on the indicators, for which the indicators are classified into three levels considering the availability of the data and the ability to update. Level I indicators are those in which we can obtain the data directly or indirectly through the methodology exposed, always from reliable sources and are periodically updated. Level II indicators collect data that is not regularly updated officially, come, for example, from specific studies. And Level III when there is no public data available or an accessible source. This classification is based on the one proposed by the Group of Experts, High-level Group for Partnership, Coordination and Capacity-Building (HLG-PCCB), to characterize the SDG indicators.

3. Results

As a result of the methodological process, a framework has been established with 7 global Brine Management Goals broken down into 11 specific targets and a total of 18 monitoring indicators. The practical case carried out quantifies the values of the indicators and their level of maturity in the selected region. This study provides a baseline on brine management, which will make it possible to assess future progress in terms of sustainability.

3.1. Goal 1: minimize the impact of the discharge on the marine environment

3.1.1. Target 1.1. Reduce the volume of brine generated

- Indicator 1.1.1. Annual volume of brine generated by seawater desalination plants (hm^3/year).

The data have been collected from the list of flows provided by the Hydrological Plans of the islands. But these reports only on the volume produced by the desalination plants with discharges greater than 0.1 hm^3/year, defined as 'persistent pressure' discharges. The information is updated approximately every six years, coinciding with the Hydrological Cycle Plans, in our case the data corresponds to 2015 at the beginning of the 2nd Hydrological Cycle.

The volume of the last available public inventory of discharges, corresponding to the year 2013, where an annual brine volume generated by seawater desalination plants of almost 250 hm^3 was estimated. Approximately 42 % of the discharge points have an annual contribution greater than 0.1 hm^3, the remaining 58 % coming from the set of plants with lower volume discharges (Table 2).

- Indicator 1.1.2. Salinity of brine discharge

The average salinity of the Canary waters is 36.5 psu (practical salinity unit) [31]. On the other hand in the Canary Islands, most desalination plants are reverse osmosis, some plants reach recovery rate values above 50 %, however, the average values are between 40 % and 45 % recovery. The salinity of the brine has been estimated based on the mean values of the recovery factor and the mean salinity of seawater (Table 3).

3.1.2. Target 1.2. Reduce the pollutant load discharged into the sea

- Indicator 1.2.1. Discharge of brine into the sea with prior dilution or joint discharge techniques (%).

We have counted discharge points registered by the Canary Islands Territorial Information System (IDECanarias) and analyzed the types of effluents. The registered discharges correspond to the last census carried out between 2016 and 2017. A total of 60 pipelines have been counted throughout the Canary Islands that discharge brine into the sea, of which 73.3 % discharge exclusively brine and 26.6 % share the point of discharge with other effluents. Joint discharge techniques help reduce the concentration, temperature, and pollutant load of both effluents (Table 4) (Fig. 2).

- Indicator 1.2.2. Discharged into the sea with underwater pipeline with diffuser section (%).

We have counted discharge points registered in the IDECanarias based on data from the census carried out between 2016 and 2017 and analyzed the discharge techniques. In the Canary Islands, approximately 53 % of brine discharges do not use underwater pipelines and 27 % use outfall with diffuser section (Table 5) (Fig. 3).

Table 3
Average recovery factor values of seawater desalination plants by island.

	Lanzarote	Fuerteventura	Gran Canaria	Tenerife	El Hierro
Recovery factor	45 %	40–44 %	45 %	45 %	43 %
Salinity estimate (psu)	66.4	60.8–65.1	66.4	66.4	64.0

Own elaboration.

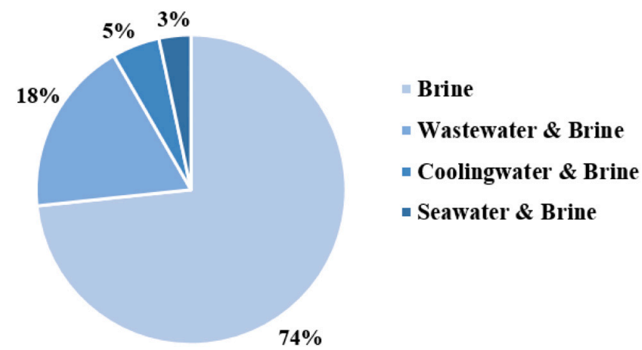

Fig. 2. Brine discharges with another effluent.

3.1.3. Target 1.3. Make use of green chemicals in the seawater desalination sector.

- Indicator 1.3.1. Green chemicals use in desalination processes (%).

Currently, there is no public information available to determine the percentage of green chemical use in the facilities considered by the case study.

3.2. Goal 2: Increase regulation and control

3.2.1. Target 2.1. Guarantee a regulation (and its compliance) that ensures the good state of the quality of the waters and ecosystems against brine discharges.

- Indicator 2.1.1. Specific regulations for brine discharges.

The analysis of the regulatory framework carried out highlights the following documents. The National Marine Strategies Plan identifies brine discharging as a point of pressure toward the seabed. In addition to recognizing the anthropic effect, the Strategies provide a series of monitoring programs for the marine environment. The Monitoring Program for benthic habitats stands out, highly sensitive to brine discharges and, in the second cycle (2018–2024), a new Program was included regarding the monitoring of brine discharges.

However, there is currently no specific legislative that define how to design and control brine discharges from land to sea at a national or regional level, only recommendations guides have been identified.

Table 2
Annual volume of brine produced in the Canary Islands, in hm^3/year.

Source:	Lanzarote	Fuerteventura	Gran Canaria	Tenerife	La Gomera	El Hierro	Total
Hydrological plans[a]	29.18	21.24	52.34	16.41	0.89[b]	1.82	105.3
Official inventory	52.86	40.49	112.94	39.65	0.89	2.43	249.26

Own elaboration.
[a] Raw data in m^3/h, estimated data considering a production of 24 h and 365 days.
[b] It has been estimated with a 45 % recovery rate.
Adapted from the 2nd Cycle Hydrological Plans (2015–2021) and other official sources with 2013 data.

Table 4
Discharge points with brine effluents into the sea.

	Lanzarote	Fuerteventura	Gran Canaria	Tenerife	La Gomera	Total	Total
Brine	3	11	23	6	1	44	73.33 %
Brine & wastewater	0	3	6	2	0	11	18.33 %
Brine & cooling water	0	0	1	2	0	3	5.00 %
Brine & seawater	0	0	1	1	0	2	3.33 %
Total by islands	3	14	31	11	1	60	100 %

Own elaboration.

Table 5
Methods used at the point of discharge of brine into the sea by island.

	Lanzarote	Fuerteventura	Gran Canaria	Tenerife	La Gomera	Total	Total
Cliff	1	0	6	1	0	8	13.33 %
Stone beach	0	6	12	4	0	22	36.66 %
Outfall without diffuser	1	4	7	0	0	12	20.00 %
Outfall with diffuser	1	4	5	5	1	16	26.66 %
Open channel	0	0	1	1	0	2	3.33 %
TOTAL by islands	3	14	31	11	1	60	100 %

Own elaboration.

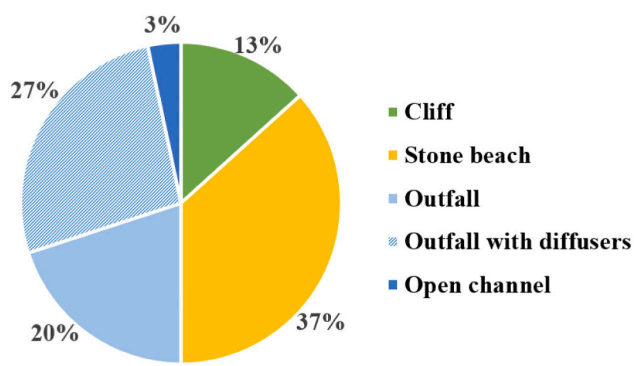

Fig. 3. Discharge systems.

- Indicator 2.1.2. Percentage of authorized discharges.

We have analyzed the legal status of the discharge points with brine effluents, registered in the 2016–2017 census. Unfortunately, about 39 % of discharge points containing brine are still not considered authorized points (Table 6) (Fig. 4).

3.2.2. Target 2.2. Guarantee the correct control and environmental monitoring of brine discharges.

- Indicator 2.2.1. Environmental Monitoring Plan (EMP) established.

The EMPs carry out the monitoring activities and their contents may vary depending on the circumstances of each region. Generically, EMPs contain indicators of the characteristics of the effluent and receiving waters, as well as indicators of the quality of sediments and organisms present in the vicinity of the discharge point, for example, it is usual to establish a maximum of 10 % in the increase in salinity with respect to the value of the receiving medium. It is important to establish biological indicators to detect the effect on the environment. *Cymodocea nodosa* is considered a promising bioindicator [32]. It is a benthic species, of great value in the Canary Islands, which is highly sensitive to changes in salinity and has a threshold of 39.5 psu.

It has been observed that 66.6 % of discharge points are subject to environmental monitoring to assess the possible effect of brine discharge

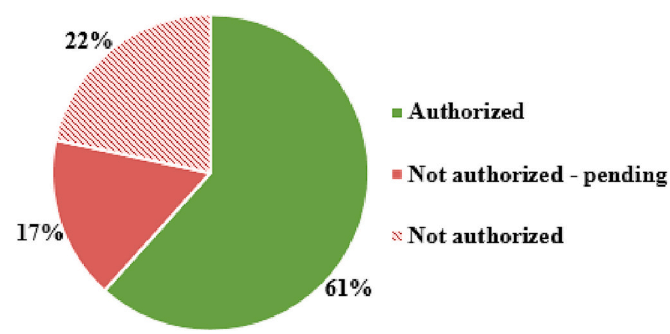

Fig. 4. Legal status of brine discharges.

Table 7
Points of discharge of brine into the sea that have an annual EMP.

Discharge point:	Authorized	Not authorized-pending	Not authorized	Total	Total
With EMP	32	7	1	40	66.6 %
Without EMP	5	3	12	20	33.3 %
TOTAL				60	100 %

Own elaboration.

Table 6
Legal status of discharge points with brine effluents into the sea.

	Lanzarote	Fuerteventura	Gran Canaria	Tenerife	La Gomera	Total	Total
Authorized	3	7	15	11	1	37	61.66 %
Not authorized-pending	0	5	5	0	0	10	16.66 %
Not authorized	0	2	11	0	0	13	21.66 %
TOTAL	3	14	31	11	1	60	100.00 %

Own elaboration.

on the quality of the water or near ecosystems (Table 7).

3.3. Goal 3: reducing CO_2

3.3.1. Target 3.1. Increase the efficiency of equipment and reduce the energy consumption of the plant.

- Indicator 3.1.1. Energy consumption associated with brine management

According to data provided by the Directorate-General for Industry (DGIE) the average specific energy consumption in the Canary Islands of a desalination plant is 4.89 kWh/m^3 including pumping and energy recovery equipment. It is interesting to mention the DESALRO 2.0 Project, whose main objective is to validate the design of a pilot SWRO desalination plant (fully designed in the Canary Islands) for its development on an industrial scale (5000 m^3/day) with specific energy consumption below 2 kWh/m^3 with energy recovery.

There are no public data available to quantify the energy consumption of brine management. However, the AQUASOST project has been started in the Canary Islands, this project will collect data on the operation of a desalination plant. The data will be stored in an open access repository that may be used for research purposes.

3.3.2. Target: 3.2: use of RR.EE. at the desalination plant

- Indicator 3.2.1. Contribution of RR.EE. in desalination plants

The annual energy supplied by renewable energy facilities linked to desalination plants has been estimated at 45.26 GWh, which represents 3.8 % of the total annual energy required by desalination in the Canary Islands (Table 8).

3.4. Goal 4: blue energy

3.4.1. Target 4.1. Search for efficient technologies to generate electricity from the saline gradient using desalination brines.

- Indicator 4.1.1. Number of pilot-scale installations.

We have detected the development of a project in order to install a pilot plant to evaluate the capabilities of FO and PRO technologies in a treatment plant located in the southeast of Gran Canaria. This project has been developed through the Desal+ project [37].

- Indicator 4.1.2. Number of installations on an industrial scale.

Table 8
Installed capacity of RR.EE. linked to desalination plants.

Desalination plants	Installed potency (MW)		Estimated annual production (GWh)	Ref.
	Wind farm	Solar farm		
La Florida-Vargas (GC)	–	–	3.62[a]	[33]
Mancomunidad (GC)	–	0.37	1.23	[34]
Bocabarranco (GC)	2.30	0.10	6.77	[35]
Roque Prieto (GC)	2.30	0.10	6.77	[35]
Arucas-Moya (GC)	–	0.38	1.25	[35]
Bonny (GC)	0.85	–	2.38	[36]
Bristol (Ftv)	1.70	–	4.76	[36]
El Charco (Ftv)	2.00	–	5.60	[36]
Díaz Rijo (Lz)	4.60	–	12.88	[36]
TOTAL			45.26	

[a] Actual production data in 2009; (GC): Gran Canaria; (Ftv): Fuerteventura; (Lz): Lanzarote. Own elaboration.

After the study, we have detected that technologies for taking advantage of the saline gradient of desalination brines have not yet been implemented on an industrial scale in the Canary Islands.

3.5. Goal 5: circular economy

3.5.1. Target 5.1. Valorization of brine to achieve its transformation from waste to resource.

- Indicator 5.1.1. Identification of uses, elements and applicability.

Two projects of interest for the development of the circular economy in the study area have been detected. The first of these concerns a study that took brine samples from five desalination plants in Tenerife and proposed its use as a source of nutrients for tomato cultivation in the Canary Islands and hydroponic crops. However, more studies are still needed to determine economic profitability [38]. The second project of interest is the Sea4Value project which explores the technical feasibility of extracting elements such as magnesium, lithium or rubidium from brine, and the project selected a desalination plant in Tenerife (Canary Islands) to locate one of its demo sites [39].

- Indicator 5.1.2. Volume of compounds from brine valued and marketed (m^3/year).

The recovery of brine is still at an early stage, and there is currently no volume of industrially recovered brine available. In addition to developing reliable technologies, these must be profitable to successfully be integrated into the sector.

- Indicator 5.1.3. Management of by-products generated.

The treatments necessary to extract or generate products of interest from the brine will also produce new by-products. It is necessary to analyze and define the way in which the new waste should be managed.

3.6. Goal 6: innovation

3.6.1. Target 6.1. Promote the development of new technologies, synergies with other industries, and public-private collaboration.

- Indicator 6.1.1. Number of patents related to new developments and technologies in desalination.

A total of 24 patents related to desalination whose owner is registered in the Canary Islands have been identified. Of these, 37.5 % have public participation and the remaining 62.5 % are exclusively private. Those related to energy stand out for their number, referring to energy saving or the coupling of RR.EE. to desalination. Highlight the patent for environmental improvement with venturi diffuser devices made by E. Portillo in 2011 and on the topic of energy the Forward Osmosis patent made by R. Falcón in 2013 (Table 9) (Fig. 5).

3.7. Goal 7: applied research

3.7.1. Target 7.1. Invest in research and development in areas directly related to desalination and especially on its sustainability.

- Indicator 7.1.1. Number of theses directly related to desalination and its sustainability.

The Canary Islands have two universities, the University of La Laguna (ULL) and the University of Las Palmas de Gran Canaria (ULPGC), with a long career in water engineering, highlighting the doctorate program in "Environmental Quality and Natural Resources", under the research strand of "Desalination and Membranes" [40]. To

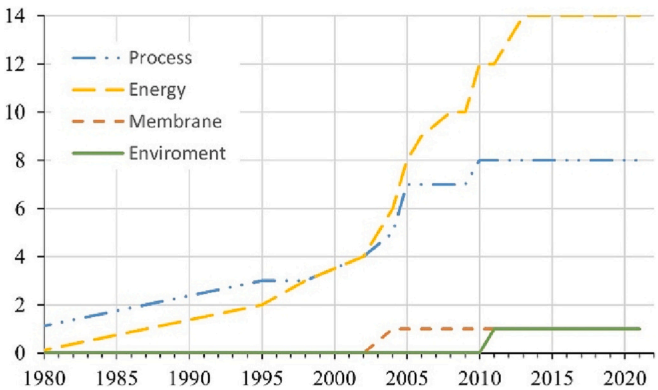

Fig. 5. Number of patents by theme, registered in Canary Islands. Own elaboration.
Adapted from OEPM.

Table 9
Summary of patents registered in the Canary Islands.

Applicant	Process	Energy	Membrane	Environment	Subtotal
University of Las Palmas de Gran Canaria	–	2	–	–	2
Canary Islands Technological Institute (ITC)	1	5	–	–	6
ITC and private company	–	–	–	1	1
Private company	7	7	1	–	15
TOTAL	8	14	1	1	24

Own elaboration.
Adapted from Spanish Patent and Trademark Office (OEPM) database.

obtain a value for the described indicator, the number of published theses from 1990 to 2021 in the two universities have been collected through their databases. A total of 23 theses have been found, which have been divided into four topics according to their main theme. The theses related to energy stand out, due to their greater number, addressing the implementation of renewable energies in desalination processes (Table 10) (Fig. 6). Due to its direct relationship with the impact of brine, one can highlight the thesis carried out in 2014 by E.F. Hahnefeld discusses the dispersion effect of brine and its effect on seagrasses.

- Indicator 7.1.2. Number of articles referring to desalination or its impacts.

A total of 155 scientific articles, written from 1998 to 2021, related to desalination have been quantified in the database of the University of Las Palmas de Gran Canaria. For this purpose, academic publications carried out by researchers associated with the university as main authors

Table 10
Summary of thesis by topic.

Topic	N° of theses	References
Process	4	[41]; [42]; [43]; [44]
Membranes	4	[45]; [46]; [47]; [48]
Environment	4	[49]; [50]; [51]; [52]
Energy	11	[53]; [54]; [55]; [56]; [57]; [58]; [59]; [60]; [61]; [62]; [63]
TOTAL	23	

Own elaboration.
Source: ULPGC and ULL database.

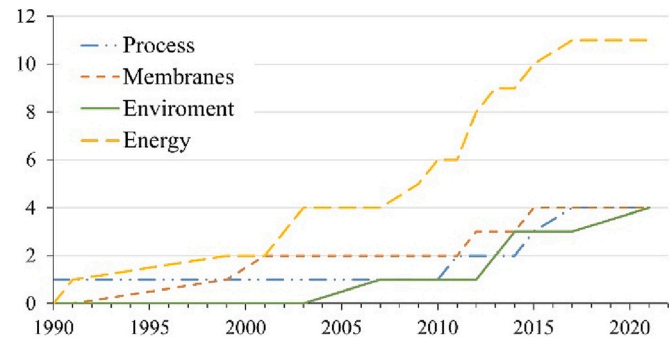

Fig. 6. Thesis by topic presented at Canary Universities. Own elaboration.
Source: ULPGC and ULL database.

have been considered. In addition, it has been completed with articles that have been the result of research and innovation projects carried out through the technological centres of the Canary Islands.

3.7.2. *Relationship analysis between SDG and BMG*

The relationship matrix created shows that brine management can have an affinity with up to eight Sustainable Development Goals. This potential relationship is represented in the following Table 11.

With the available data, for each indicator, a qualitative assessment of progress was made in the period from 2015 to the present. The first two BMGs were not extracted from historical data for analysis. With regard to research, it is considered that there have been contributions in all areas, however, in the last seven years these have not been transformed into results in the form of patents, the main indicator of the innovation goal (Table 12).

4. Discussion

While the SDGs offer a unique opportunity to bring together corporate and governmental efforts for sustainable development, there is also criticism of the assessment of actions taken to achieve the SDGs. Their achievement is expected to take place within an implementation framework based on monitoring, evaluation and impact assessment and, to a large extent, on attempts to align the activities of multiple actors through coordination, such as joint strategies and visions [64].

The paper proposes a new approach to integrating brine management strategies into sustainable development goals, identifying and visualizing their relationship in a simple, understandable and practical way. The framework described above contains seven main goals or pillars that can be grouped into three blocks or dimensions: the traditional goals, the new challenges and the transversal goals.

The first dimension includes traditional impact management strategies. We refer to the '*BMG-1 Minimize impact of the discharge*', '*BMG-2 Regulation & Control*' and '*BMG-3: reducing* CO_2', where its purpose is to minimize the direct impact produced by desalination plants and their discharge.

CO_2 emissions along with the degradation of marine ecosystems are the two most important impacts of the desalination industry. While it is true that the impact of CO_2 emissions is not attributable to the desalination plant itself but to the energy producer, it is the responsibility of the plant to reduce its energy consumption or integrate renewable energies into the processes. Commonly, brine management is only associated with the impact derived from its discharge. However, it should be noted that brine management techniques such as predilution require additional energy consumption in pumping equipment. In addition, the treatment of brine necessary for the recovery of elements requires greater energy consumption, in this case, that of the circular economy the correlation between the energy consumed and the management of brine becomes important. On the contrary, Energy recovery devices (ERD), which involve brine flow, reduce energy consumption in SWRO

Table 11
Summary of relationship between BMGs and SDGs. Own elaboration.

	SDG 6 Clean water and sanitation	SDG 7 Affordable and clean energy	SDG 8 Decent work and economic growth	SDG 9 Industry, innovation and infrastructure	SDG 12 Responsible, consumption and production	SDG 13 Climate action	SDG 14 Life below water	SDG 17 Partnerships for the goals
BMG 1: Impact of the discharge	-			-	-		-	
BMG 2: Regulation & Control	-		-	-	-		-	-
BMG 3: Reducing CO_2		↗		↗				
BMG 4: Blue energy		↗		↗		-		
BMG 5: Circular economy			-	-				
BMG 6: Innovation	→	→	→	→	-	→	→	→
BMG 7: Applied Research	↗	↗	↗	↗	↗	↗	↗	↗

Table 12
Summary of proposed goals, targets and indicators and their results in the Canary Islands.

Goals	Targets	Indicators	Level	Data	Base	Source
1. Minimize the impact of the discharge on the marine environment	1.1. Reduce the volume of brine discharged into the sea.	1.1.1 Volume of brine discharged into the sea per year (hm^3/year)	I	249.26	2013	Official inventory
		1.1.2 Salinity of brine discharge (psu)	I	60.8–66.4	2012	Hydrological Plans
	1.2. Reduce the pollutant load discharged into the sea	1.2.1. Percentage of brine discharge points into the sea with prior dilution.	I	26.6 %	2016	IDE-Canarias
		1.2.2. Submarine outfalls with diffuser section.	I	26.6 %	2016	IDE-Canarias
	1.3. Eliminate harmful compounds from the discharged brine.	1.3.1 Use of Green Chemicals	III	–	–	Exploring data source
2. Regulation and control of discharge	2.1. Guarantee regulations that ensure the good state of the quality of waters and ecosystems.	2.1.1. Specific regulations for brine discharges at the regional level.	I	0	2022	Canary Islands Government
		2.1.2 Authorized discharges	I	61.6 %	2016	IDE-Canarias
	2.2. Guarantee the correct control and environmental monitoring of brine discharges.	2.2.1. Percentage of Environmental Monitoring Plans	I	66.6 %	2016	IDE-Canarias
3. Reducing CO_2	3.1. Increase the efficiency of the desalination plant	3.1.1. Energy consumption associated with brine management (kWh/m^3)	III	–	–	Exploring data source
	3.2. Use of RR.EE. at the desalination plant	3.1.2 Contribution of RR.EE. at the desalination plants	II	3.8 %	2022	Various sources
4. Blue Energy	4.1 Search for technologies to use natural osmotic pressure with desalination brine	4.1.1. Number of pilot scale installations	II	1	2022	Desal+ web
		4.1.2. Number of installations on an industrial scale	II	0	2022	Various public sources
5. Circular Economy	5.1. Valorization of brine, achieve its transformation from waste to resource.	5.1.1. Identification of elements, applicability and quantification.	III	–	–	Exploring data source
		5.1.2 Volume of compounds on the market per year (m^3/year)	III	–	–	Exploring data source
		5.1.3. Management of by-products generated.	III	–	–	Exploring data source
6. Innovation	6.1 Promote innovation, synergy with other industries and Public-Private collaboration	6.1.1. Number of patents related to desalination	I	24	2021	OEPM
7. Applied research	7.1 Expand knowledge about desalination and the effect brine has on marine ecosystems.	7.1.1. Number of theses	I	23	2021	ULL; ULPGC;
		7.1.2. Number of academic publications	I	155	2021	ULPGC database

Own elaboration.

desalination plants. Despite the important relationship between desalinated water and energy, there is a need to expand the knowledge between energy consumption and brine management.

The next dimension represents the new challenges of sustainable brine management, '*BMG-4 Blue Energy*' and '*BMG-5 Circular Economy*'. The development of strategies in pursuit of these goals could generate substantial changes in the desalination industry, however, they are still at an early stage. This article shows the relevance of these new technologies in advancing a more sustainable model of development.

The last dimension is transversal and includes the goals '*BMG-6 Innovation*' and '*BMG-7 Applied Research*'. These are the knowledge base and add value to each of the above goals, for example, studies on the tolerance thresholds of marine species to the increase in salinity in the environment due to the discharge of brine, serve as a reference to establish discharge limits in regulations and establish control values. Knowledge generation is an activity that is often forgotten as a brine management strategy, and it is important to highlight its place in the value chain as it is the basis for future actions.

Brine Management Goals have been linked to eight of the seventeen SDGs (Table 11). As shown in Table 11, the SGD of 'Industry, innovation and infrastructure' (SDG 9) is cross-cutting, being displayed in all BMGs. Traditional management strategies are more linked to Clean Water (SDG 6), Responsible Production (SDG 12) or Life under the sea (SDG 14). However, the most innovative strategies such as blue energy, in the context of brine management, are related to clean energy (SDG 17) or actions for climate change (SDG 13). Finally, the goals on Innovation and Research are presented in the eight selected SDGs. It should be noted that when establishing a brine management strategy, the crucial point is not to tackle the greatest possible number of SDGs but instead develop and implement an holistic approach through which the achievement of the selected goal(s) does not negatively affect the others.

The assessment and monitoring of this interaction is carried out thanks to the quantification of the proposed indicators. In the practical case, it defines the baseline, that is, the initial values that will serve as a reference in future studies (Table 12). In addition to providing the reference value, the study classified the indicators by their level of maturity.

The results show how the Canary Islands region is investing in a strategy that mainly promotes SDG 7, Clean and affordable energy, and SDG 9, Industry, innovation and infrastructure. In addition, the generation of knowledge, through publications, is a key pillar having the greatest impact on the set of SDGs. It is expected that the number of theses and academic publications will increase, in addition to increasing installations with innovative technologies (Figs. 5 and 6). Nevertheless, this effort has not yet been reflected in the increase in the number of patents in the last ten years, the main indicator of the innovation strategy.

On the other hand, the public information available regarding brine management is very scarce, and the lack of accessibility or updating of the data regarding the operation, management of the plants, or their environmental monitoring has not allowed the evaluation of traditional strategies (BMG 1, BMG 2 and BMG 3) and their contribution to the SDG commitments. However, it is observed that the percentage of environmental monitoring plans is higher than the percentage of authorized discharges; this is because the operating companies implement environmental monitoring measures even though they do not have the final administrative authorisation.

Concerning the level of maturity of the indicators, in the study region, the indicators classified in level I account for 59 % of the total defined indicators. Level I indicators have been obtained thanks to the processing of different databases of official information sources, unfortunately the periodicity and updating of the data present different time scales and it is not possible to have the same database year or the same data update frequency, these will make it difficult to monitor the indicators together. It is complicated to obtain raw data in the same measurement units, and some assumptions must be established to standardize them. For instance, in the case of indicators that represent consumption or production, It would be of great value to have more detailed public information on the results of the management of the desalination plants and offer greater homogeneity in the representation of the data.

Level II indicators represent 12 % of the total number of identified indicators. Level II indicators focus on the *BMG-3 reducing* CO_2 and *BMG-4 Blue Energy* goals. These goals coincide with non-traditional management strategies so that there are still no official databases that centralize information. But in addition, it is shown with the graph of progress of theses and patents made that the topic of energy is the one that presents the greatest interest, therefore the level of maturity obtained in the indicator is consistent with the rest of the results of the study.

The measures to reduce CO_2 begin by promoting the saving, reuse and responsible consumption of water on the islands. Equally important is the need to reduce the energy consumption of desalination plants and develop the implementation of renewable energies and their degree of penetration. The Canary Islands have a high potential for solar and wind energy; its application to desalination is the subject of continuous studies and very promising experimental tests. However, the direct application to the desalination process is not yet fully developed for large and medium production capacities [65]. In spite of this, the archipelago has extensive experience in the energy optimization of desalination plants, incorporating technologies such as energy recovery devices, the most widespread being isobaric chambers based on rotary displacement devices, due to their robustness and modularity [66]. In the Canary Islands, 10 % of primary energy is used to desalinate water, which represents 35 % of the water consumed. These data make visible the importance of the energy-desalination nexus. The results of our study show that 3.8 %. of energy consumed by desalination comes directly from RE facilities integrated into the plant. The biggest current challenge is the application of RR.EE. In large desalination plants, which must ensure a constant homogeneous quality of the product water. Another relevant challenge for desalination is the use of marine renewable energy in future designs.

In the last level, the indicators at level III remaining 29 %. This is the case with the indicators of the Circular Economy and the use of green chemicals. As can be seen, the major difficulty is that these are the most innovative technologies, the industry is still integrating them and they have not yet reached a state of maturity in the sector. The institutions and companies in the sector should carry out an exercise of transparency and accessibility of information, to obtain representative indicators.

In this article, a single level of hierarchy has been established in the indicators, however, it is possible to incorporate sub-indicators that provide more in-depth information. To obtain a more detailed scenario, new representative indicators should continue to be explored. The proposal made in this document does not assign results and deadlines to be met in the indicators but instead points out a course for the competent institutions to take the proposal and adapt it to their needs and level of commitment.

5. Conclusions

The production of desalinated water, and therefore brine, is expected to increase in the coming decades in response to the climate crisis. The industry is making efforts to advance technically toward more sustainable desalination. Developing new technologies and strategies for sustainable brine management has become a necessity. However, it is complex to compare and evaluate the sustainability level achieved or the effectiveness of the environmental improvement strategies adopted.

The article achieves the integration of brine management strategies with Sustainable Development Goals through the proposal of a framework of seven management goals, broken down into eleven targets, which integrate brine management strategies for more sustainability. In addition, the author proposes seventeen indicators for monitoring the goals. These indicators are quantified and classified according to their level of maturity in a practical case for the Canary Islands region.

It is the first time that brine is treated as a product with a value chain that entails the generation of knowledge, the regulatory framework, the treatment of brine in the plant, its new use (recognizing new management tools such as the Circular Economy and Blue Energy), its discharge, and associated environmental monitoring. This approach makes it possible to incorporate the application of the SDGs in the analysis of the environmental management of industrial facilities.

The proposed new approach classifies brine management in terms of its achievements rather than its means, this makes it possible to evaluate various management strategies on the same plane. Another benefit of goal classification is its timelessness, unlike technology classification which can vary over time.

This holistic vision of the management, the framework developed in this work, allows for raising the level of management from the plant to the territory. Through the territory approach, it is possible to incorporate, in brine management, the contributions of different actors - such as public institutions, universities or knowledge centres. This approach highlights the capabilities and responsibilities of public administrations and environmental protection agencies for the progress of a sustainable management model.

Integrating brine management strategies with the SDGs provides a common framework for directing resources and aligning actions. The study shows the possibility of relating brine management strategies to up to eight of the seventeen SDGs, with SDG 9 ‘Industry, innovation and infrastructure’ being the most frequent and the Brine Management Goals on Innovation (BMG 6) and Applied Research (BMG 7) being the ones with the greatest impact. At the same time, one should not forget that the more traditional strategies, such as minimizing the impact of discharges and their regulation and control, must continue to improve and be updated in the light of technology and knowledge evolution.

The proposed BMG-SDG relationship matrix can help decision-makers to select the most sustainable desalination technology with economic and environmental considerations. The integration of the SDGs in projects is already a key factor in calls for public financing and aligning business strategies with the SDGs will be a necessity, not an option, for example, due to regulatory requirements or to meet investor expectations and shareholders. The implementation of the SDGs must be a transformation that is present in decision-making, policies and management tools. However, there is still a long way to go, we are at a crucial moment to reflect on the SDGs. This paper presents an approach that feeds into the debates on the SDGs and their implementation in a novel way and bridges the gap between the academic and the political.

In addition, the paper establishes specific indicator elements for brine management, laying the foundations for integrating sustainable brine management strategies into the SDGs. The results of the practical case show how the Canary Islands have adopted a strategy based on the development of the water-energy nexus, highlighting the efforts for the integration of renewable energies in desalination plants, the number of theses, publications and patents related to energy in desalination. However, in recent years no new patents, nor projects, have been registered that shows the implementation of this knowledge in the market on an industrial scale. On the other hand, the importance of digitizing the processing of sector data to provide accessibility and transparency regarding the management carried out has become evident. The Canary Islands have the possibility of leading the way for a more sustainable desalination model and continue to demonstrate their ability to be a pioneer in the integration of the SDGs in environmental management.

It is recommended to periodically monitor the indicators of the case study, analyzing the progress or setback of the defined goals and objectives. It is decisive that public administrations adopt the methodological procedures and the proposed tools, adding realistic dates to the objectives and establishing compliance ratios according to their degree of commitment. It is also recommended to increase the accessibility of data on the discharge and operation of desalination plants.

The ambition for sustainable development is an ongoing task that must be constantly evaluated, thus it is recommended to replicate the methodology with other case studies in different regions, allowing the level of sustainability between cases and their management and development strategies to be compared. Furthermore, to achieve different perspectives, it is advisable to replicate the methodology at different scales of study, at the national level by increasing the scale or at the company or treatment plant level by reducing the scale.

Finally, it is suggested that the developed methodology shall be adapted to the environmental management of other industries, such as the treatment of wastewater or reclaimed water, defining a new framework of sustainability goals that encompass future actions to better protect the environment.

CRediT authorship contribution statement

Adrián Gil Trujillo: PhD student in Environmental Quality and Natural Resources Program (DOCARNA).

J. Jaime Sadhwani Alonso: Thesis Director.

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.

References

[1] E. Jones, M. Qadir, M.T.V. Vliet, V. Smakhtin, Seong-Mu Kang, The state of desalination and brine production: a global outlook, Sci. Total Environ. 657 (2019) 1343–1356.
[2] Argyris Panagopoulos, Katherine-Joanne Haralambous, Maria Loizidou, Desalination brine disposal methods and treatment technologies -a review, Sci. Total Environ. (693) (2019).
[3] Musthafa O. Mavukkandy, Ch.ahd.M. Chabib, Ibrahim Mustafa, Amal Al Ghaferi, Faisal AlMarzooqi, Brine management in desalination industry: from waste to resources generation, Desalination 472 (2019).
[4] Hila Frank, Katarina E. Fussmann, Eyal Rahav, Edo BarZeev, Chronic effects of brine discharge form large-scale seawater reverse osmosis desalination facilities on benthic bacteria, Water Res. 151 (2019) 478–487.
[5] Karen Lykkebo Petersen, E. Adina Paytan, Oren Levy Rahav, Oriya Barzel JacobSilverman, Donald Potts, Edo Bar-Zeev, Impact of brine and antiscalants on reef-building corals in the Gulf of Aqaba e potential effects from desalination plants, Water Res. 144 (2018) 183–191.
[6] Marion L. Cam-bridge, Andrea Zavala-Perez, Greg R. Cawthray, John Statton, Julie Mondon, Gary A. Kendrick, Effects of desalination brine and seawater with the same elevated salinity on growth, physiology and seedling development of the seagrass Posidonia australis, Mar. Pollut. Bull. 190 (2019) 462–471.
[7] Biplob Kumar Pramanik, Li Shu, Veeriah Jegatheesan, A review of the management and treatment of brine solutions, Environ. Sci.: Water Res. Technol. 625 (2017).
[8] Nurit Kress, Yaron Gertner, Efrat Shoham-Frider, Seawater quality at the brine discharge site from two mega size seawater reverse osmosis desalination plants in Israel (Eastern Mediterranean), Water Res. 171 (2020).
[9] Mohamed O. Saeed, M.I.Mohamed Ershath, Brahim A. Al-Tisan, Perspective on desalination discharges and coastal environments of the Arabian Peninsula, Mar. Environ. Res. (145) (2019) 1–10.
[10] I. Sola, D. Zarzo, A. Carratalá, Y. Fernández-Torquemada, J.A. de-la-Ossa-Carretero, Y. Del-Pilar-Ruso, J.L. Sánchez-Lizaso, Review of the management of brine discharges in Spain, Ocean Coast. Manag. 196 (2020).
[11] Raed Bashitialshaaer, Kenneth M. Persson, Developing new measuring technique controlling desalination brine concentration, in: The International Desalination Association World Congress on Desalination and Water Reuse, REF: IDAWC15-Bash, 2015.
[12] I. Sola, D. Zarzo, J.L. Sánchez-Lizaso, Evaluating environmental requirements for the management of brine discharges in Spain, Desalination 471 (2019).
[13] Jin Zhou, Victor W.-C. Chang, Anthony G. Fane, Life cycle assessment for desalination: a review on methodology feasibility and reliability, Water Res. 61 (2014) 210–223, https://doi.org/10.1016/j.watres.2014.05.017.
[14] Adewale S. Bello, Nabil Zouari, Dana A. Da'ana, John N. Hahladakis, Mohammad A. Al-Ghouti, An overview of brine management: emerging desalination technologies, life cycle assessment, and metal recovery methodologies, J. Environ. Manag. 288 (2021).
[15] Nur Izzah Hamna, A. Aziz, Marlia M. Hanafiah, Application of life cycle assessment for desalination: progress, challenges and future directions, Environ. Pollut. 268 (2021), https://doi.org/10.1016/j.envpol.2020.115948.
[16] Xu. Pei, Tzahi Y. Cath, Alexander P. Robertson, Martin Reinhard, James O. Leckie, Jörg E. Drewes, Critical review of desalination concentrate management, treatment and beneficial use, Environ. Eng. Sci. 30 (8) (2013) pp.
[17] E. Portillo, G. Louzara, M. Ruiz de la Rosa, J. Quesada, J. Gonzalez, F. Roque, M. Antequera, H. Mendoza, Venturi diffusers as enhancing devices for the dilution process in desalination plant brine discharges, Desalin. Water Treat. (2012), https://doi.org/10.1080/19443994.2012.694218.
[18] I. Shrivastava, E. Adams, B. Al-Anzi, A. Chow, J. Han, Confined plunging liquid jets for dilution of brine from desalination plants, Processes 9 (856) (2021), https://doi.org/10.3390/pr9050856.
[19] Nikolay Voutchkov, Gisela Kaiser, Richard Stover, John Lienhart, Leon Awerbuch, Sustainable management of desalination plant concentrate - desalination industry position paper – energy and environment committee of the International Desalination Association (IDA), in: The International Desalination Association World Congress on Desalination and Water Reuse, UAE REF: IDAWC19-Voutchkov, 2019.
[20] A. Giwa, V. Dufour, F. Al Marzooqi, M. Al Kaabi, S. Hasan, Brine management methods: recent innovations and current status, Desalination 407 (2017).
[21] Pilar Palomar, Iñigo J. Losada, in: Michael Schorr (Ed.), Impacts of Brine Discharge on the Marine Environment. Modelling as a Predictive Tool, Desalination, Trends and Technologies, 2011. ISBN: 978-953-307-311-8.
[22] Y. Ibrahim, H.A. Arafat, T. Mezher, F. AlMarzooqi, An integrated framework for sustainability assessment of seawater desalination, Desalination 447 (2018).
[23] Jawad Mustafa, Aya A.-H.I. Mourad, Ali H. Al-Marzouqi, Muftah H. El-Naas, Simultaneous treatment of reject brine and capture of carbon dioxide: a comprehensive review, Desalination 483 (2020).
[24] Jochen Bundschuh, Michał Kaczmarczyk, Noreddine Ghaffour, Barbara Tomaszewska, State-of-the-art of renewable energy sources used in water desalination: present and future prospects, Desalination 508 (2021).
[25] M. Mohammadifakhr, J.D. Grooth, H.D.W. Roesink, A.J.B. Kemperman, Forward osmosis: a critical review, Processes 8 (2020) 404, https://doi.org/10.3390/pr8040404.

[26] N. Melián-Martel, J.S. Alonso, S.P. Báez, Reuse and management of brine in sustainable SWRO desalination plants, Desalin. Water Treat. 51 (560–566) (2013).
[27] José Morillo, José Usero, Daniel Rosado, Hicham El Bakouri, Abel Riaza, Francisco-Javier Bernaola, Comparative study of brine management technologies for desalination plants, Desalination 336 (2014) 32–49.
[28] Fernando Rodríguez-DeLaNuez, Nut Franquiz-Suárez, Dunia Esther Santiago, José Miguel Veza, Jose Jaime Sadhwani, Reuse and minimization of desalination brines: a review of alternatives, Desalin. Water Treat. 39 (2012) 137–148.
[29] Enrique Rosales-Asensio, Francisco Jose Garcia-Moya, Alberto Gonzalez-Martinez, David Borge-Diez, Miguel de Simon-Martin, Stress mitigation of conventional water resources in water-scarce areas through the use of renewable energy powered desalination plants: an application to the Canary Island, Energy Rep. 6 (2020) 124–135.
[30] Federico Leon, Alejandro Ramos-Martin, Sebastian Ovidio Perez-Baez, Study of the ecological footprint and carbon footprint in a reverse osmosis sea water desalination plant, Membranes (2021), https://doi.org/10.3390/membranes11060377.
[31] Ministry for the Ecological Transition and the Demographic Challenge (MITECO), "Marine Strategy Canarian Marine Demarcation, Part I," Madrid, 2012.
[32] Vasillis Papathanasiou, Sotiris Orfanidis, Murray T. Brown, Cymodocea nodosa metrics as bioindicators of anthropogenic stress in N. Aegean, greek coastal waters, Ecol. Indic. 63 (2016) 61–70, https://doi.org/10.1016/j.ecolind.2015.11.059.
[33] Juan Blas Lozano Ruano, ISLHágua. http://www.islhagua.itccanarias.org/web/guest/jornada-tecnica-intercambio-experienciencias-agua_canarias-cabo-verde1. (Accessed 10 December 2022).
[34] Greening smart energy solutions [Online]. Available: https://greening-e.com/instalacion-de-plantas-fotovoltaicas-para-autoconsumo-en-la-depuradora-y-desaladora-del-sureste-de-gran-canaria/. (Accessed 5 February 2022).
[35] Canary Island Development Fund, Renewable energies in hydraulic infrastructures [Online]. Available: https://www3.gobiernodecanarias.org/presidencia/fdcan/project/energias-renovables-en-infraestructuras-hidraulicas/. (Accessed 20 March 2022).
[36] Government of the Canary Islands, "Energy Yearbook of the Canary Islands 2020".
[37] Desal+ project [Online]. Available: https://www.desalinationlab.com/proyectodesal+/es/resultados/97-resultados/161-proyecto-demostrativo-de-osmosis-directa-fo-en-la-depuradora-del-sureste-de-gran-canaria-mansureste-1 [Accessed february 2022].
[38] D. Jiménez-Arias, Sarai-Morales Sierra, Fráncisco J. García-Machado, A.L. García-García, A.A. Borges, J.C. Luis, Exploring the agricultural reutilisation of desalination reject brine from reverse osmosis technology, Desalination 529 (115644) (2022).
[39] Sea4value project [Online]. Available: https://sea4value.eu/converting-waste-from-seawater-desalination-plants-into-a-source-of-raw-materials/, february 2022.
[40] Antonio Gómez-Gotor, B.Del Río-Gamero, I.Prieto Prado, A. Casañas, The history of desalination in the Canary Islands, Desalination 428 (2018) 86–107.
[41] José Miguel Veza Iglesias, Thesis - Study of Evaporation Processes for Their Application in Water Desalination, University of Las Palmas de Gran Canaria, 1990.
[42] Manuel Enrique Ruiz Saavedra, Thesis: membrane process analysis - brackish water desalination, University of Las Palmas de Gran Canaria, 2011. http://hdl.handle.net/10553/7140.
[43] Noemí Melián Martell, Thesis: evaluation and characterisation of reverse osmosis membranes fouling with combination of fouling agents, University of Las Palmas de Gran Canaria, 2015. http://hdl.handle.net/10553/17090.
[44] A.Ruiz García, Thesis: design of brackish water desalination systems by reverse osmosis, University of Las Palmas de Gran Canaria, 2017. http://hdl.handle.net/10553/25872.
[45] J.Jaime Sadhwani Alonso, Thesis: study of cleansing systems in reverse osmosis membranes, University of Las Palmas de Gran Canaria, 1999. http://hdl.handle.net/10553/2111.
[46] Aldo Muñoz Elguera, Thesis: analysis and optimization of the control of the fouling processes of the reverse osmosis membranes in seawater desalination plants, University of Las Palmas de Gran Canaria, 2001. http://hdl.handle.net/10553/60868.
[47] Celso Argudo Espinoza, Thesis: overall conception and experimental implementation of membrane processes in waste water reuse, University of Las Palmas de Gran Canaria, 2012. http://hdl.handle.net/10553/7740.
[48] M.Hernández Navarro, Thesis: fouling characterisation in ultrafiltration membranes throuh strength parameters in cross flow operation, University of Las Palmas de Gran Canaria, 2015. http://hdl.handle.net/10553/17087.
[49] Felipe Correa Diaz, Thesis: evaluation of sustainability of seawater desalination plants in Northwest Mexico, University of Las Palmas de Gran Canaria, 2007. http://hdl.handle.net/10553/2082.
[50] María Fátima Campos García, Thesis: The Ecological Footprint of industrial water in island territories: sustainability versus resilience, University of Las Palmas de Gran Canaria, 2013. http://hdl.handle.net/10553/11536.
[51] Eduardo Fernando Portillo Hahnefeld, Thesis: dilution and dispersion of Gran Canaria desalination plant brine discharge: influence on seagrass meadows and potential corrective measures, University of Las Palmas de Gran Canaria, 2014. http://hdl.handle.net/10553/12134.
[52] Federico León Zerpa, Thesis: energy efficiency in seawater reverse osmosis desalination plants, University of Las Palmas de Gran Canaria, 2021. http://hdl.handle.net/10553/105761.
[53] José Antonio Carta González, Thesis: technical-economic optimization of desalination systems powered by wind energy: application to the Canary Islands, University of Las Palmas de Gran Canaria, 1991. http://hdl.handle.net/10553/61141.
[54] L.García Rodríguez, Thesis: thermoeconomic study of seawater desalination using parabolic trough collectors, University of La Laguna, 1999. http://absysnetweb.bbtk.ull.es/cgi-bin/abnetopac?TITN=192497.
[55] M.Lemine Ould Fagel, Thesis: use of wind energy for water desalination in the north of Mauritania: application to the Wilaya of Dakhlet Nouadhibou, University of Las Palmas de Gran Canaria, 2003. http://hdl.handle.net/10553/61657.
[56] V.José Romero Tenenero, Thesis: thermoeconomic analysis of seawater desalination by reverse osmosis with application of wind energy, University of La Laguna, 2003. http://absysnetweb.bbtk.ull.es/cgi-bin/abnetopac?TITN=266926.
[57] A.Manuel Delgado Torres, L.García Rodríguez, Thesis: preliminary design of a desalination system by reverse osmosis using solar thermal energy, University of La Laguna, 2009. http://riull.ull.es/xmlui/handle/915/10216.
[58] Gerardo Arancibia Moreno, Thesis: desalination and renewable energies: contribution of the technological experiences of the Canary Islands to the development of proposals applicable to the water needs of Chile, University of La Laguna, 2010. http://absysnetweb.bbtk.ull.es/cgi-bin/abnetopac?TITN=451784.
[59] Deivis Avila Prats, Thesis: optimization of hybrid systems based on renewable energies for the supply of energy to desalination plants by reverse osmosis, in the Canary Islands, University of La Laguna, 2012. http://absysnetweb.bbtk.ull.es/cgi-bin/abnetopac?TITN=503771.
[60] F.Javier García Latorre, Thesis: analysis and simulation of reverse osmosis technology in non-conventional energy resources, University of Las Palmas de Gran Canaria, 2012. http://hdl.handle.net/10553/9742.
[61] J.Juan Feo García, Thesis: cost optimisation of production lines in Sea Water desalination Plants through Reverse Osmosis in the Canary Islands, University of Las Palmas de Gran Canaria, 2013. http://hdl.handle.net/10553/11533.
[62] F.San Luis Gutierrez, I.Padrón Armas, Thesis: modeling of renewable energy systems to supply desalination plants on the island of Tenerife, University of La Laguna, 2015. https://puntoq.ull.es/permalink/f/6auhvr/ullabsysULL00592664c-3.
[63] Pedro Jesús Cabrera Santana, Thesis: smart management of a wind-powered reverse osmosis desalination system, University of Las Palmas de Gran Canaria, 2017. http://hdl.handle.net/10553/55197.
[64] Katrin Hummel, Manuel Szekely, Disclosure on the sustainable development goals – evidence from Europe, Account. Eur. 19 (1) (2022) 152–189, https://doi.org/10.1080/17449480.2021.1894347.
[65] J. Jaime Sadhwani, M. Sagaseta de Ilurdoz, Primary energy consumption in desalination: the case of gran canaria, Desalination 452 (2019) 219–229.
[66] Sigrid Arenas Urrea, Felipe Díaz Reyes, Baltasar Peñate Suárez, Juan A. de la Fuente Bencomo, Technical review, evaluation and efficiency of energy recovery devices installed in the Canary Islands desalination plants, Desalination 450 (2019) 54–63.