Sustainability assessment of a sequential anaerobic-algal membrane bioreactor for wastewater reuse

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ABSTRACT

Reused wastewater is a robust alternative to freshwater resource depletion. While high-level treatment is required, the United Nation's Sustainable Development Goals promote the recovery of resources such as energy and nutrients. Advanced wastewater treatment technologies able to recover water, energy and nutrients have been previously assessed from a life cycle perspective. This study evaluates a sequential Anaerobic-Algal Membrane Bioreactor (A^2MBR) as an alternative reuse technology. Following the Integrative Concept of Sustainability framework, 19 indicators evaluated the sustainability of an A^2MBR in Central Chile as an implementation example. Additional water supply and nutrient recovery in biosolids are key environmental benefits for the case-study. Global warming, eutrophication, and acidification potential indicators improved in the A^2MBR system vs the *status quo*. On-site treatment costs seemed competitive compared to existing alternatives to water supply (i.e., desalination) while reducing the net demand for fossil fuels due to waste transportation. Pilot demonstrations and a long-term social assessment are needed to validate the identified sustainability benefits.

1. Introduction

While millions live in water-stressed areas worldwide, 44 % of the world's wastewater is continuously discharged into the environment without treatment (UN, 2023). Revalorization of wastewater is key to countering the depletion of freshwater resources through reuse practices, recovering renewable energy in waste biomass, and coping with the scaling demand for crop fertilization. Advanced treatment technologies, such as Membrane Bioreactors (MBRs), can enhance water quality up to direct reuse standards while enabling the recovery of valuable resources like nutrients and energy (Yang et al., 2020). For instance, a sequential Anaerobic and Algal Membrane Bioreactor (A^2MBR) system is a multipurpose technology suitable for decentralized applications, capable of recovering biogas, nutrients, algal biomass, and purified water (Prieto, 2011). It consists of two phases: an anaerobic membrane bioreactor (AnMBR), responsible for reducing the biological load of the wastewater, and a algal photo membrane bioreactor (APMBR) as a nutrient polishing stage. Multipurpose technologies can facilitate resource recovery from wastewater, foster sustainable water resource management, and contribute to food security, energy production, and climate change mitigation efforts (Smol et al., 2020). However, the sustainability aspects above should be further analyzed when proposing new fit-for-purpose technologies in the face of water scarcity and climate change (Capodaglio, 2020).

Aiming to understand, from a sustainability perspective, the potential opportunities and challenges associated with the implementation of wastewater reuse projects using advanced membrane technologies, we develop a sustainability assessment for applying a multi-purpose technology, namely A^2MBR, for direct water reuse applications. For this purpose, we apply the Integrative Concept of Sustainability (ICoS), which is founded on three goals that facilitate a dynamic understanding of sustainability across diverse societal systems and cultures, enabling reflections to govern societal transformation processes (Kopfmüller et al., 2001). This study evaluates the sustainability of the implementation of the A^2MBR in a water-stressed and tourist-intensive location in Central Chile. Although the ICoS framework has been effectively applied in prior studies within the water treatment sector, its application to evaluate water reuse technologies in Chile remains unexplored. By

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employing the ICoS framework and its relevant indicators, we also identify the potential strengths and weaknesses associated with using these indicators in wastewater reuse projects for membrane technologies. To the best of our knowledge, this study is the first to identify a set of ICoS sustainability indicators for applying membrane-based technologies in wastewater reuse and further recovery of other materials, such as nutrients and energy. The applied methodology is transferable to other regions around the globe.

This study is organized as follows: Section 2 includes a literature review. Section 3 describes the study case and the A^{2}MBR technical system in detail. In section 4, results from the system's sustainability under review are analyzed through ICoS, defining the assessment criteria and indicators for a sustainable system. Section 5 summarizes the conclusions of this study.

2. Literature review

Multipurpose wastewater treatment technologies are crucial in addressing the growing demand for clean water and effective waste management, as they enable the recovery of valuable byproducts, such as renewable energy, fertilizers, and recycled water, thereby contributing to a more sustainable and circular economy (Smol, 2023). Membrane bioreactors (MBRs) are a prime example, as they combine biological treatment with membrane filtration to produce high-quality effluent while reducing overall waste discharge (Kehrein et al., 2020). Integrating membrane systems with processes such as anaerobic digestion and algal cultivation can further enhance the recovery of energy and nutrients from wastewater, closing the water-energy-nutrient loop. The use of membranes together with anaerobic digestion (i.e., AnMBRs), has been evaluated by several authors as a feasible alternative for sewage treatment and wastewater reuse (Kim and Criddle, 2023; Robles Martínez et al., 2021), as they are able of removing a broad range of contaminants from wastewater while recovering energy in biogas (Aslam et al., 2022). Nutrient-rich effluents from the anaerobic process may even be used for fertigation; however, polishing steps are required when onsite reuse is not feasible. Using membrane filtration coupled with algal treatment provides excellent results in terms of retention of cell and high-quality effluent (Benner et al., 2022; Marbelia et al., 2014).

More innovative approaches that combine Anaerobic and Algal Membrane Bioreactor (A^{2}MBR) (Prieto, 2011), are potential treatment alternatives for water reuse purposes. It consists of two phases: an AnMBR, which is responsible for reducing the biological load of the wastewater, and an algal photo membrane bioreactor (APMBR), where the excess nutrients from the previous phase are removed. The A^{2}MBR system is a multipurpose technology suitable for decentralized applications, capable of recovering biogas, nutrients, algal biomass, and purified water (Prieto, 2011). The concept of the circular economy can be applied to wastewater treatment, reflecting a paradigm shift away from viewing wastewater as a polluting waste stream and towards recognizing it as a valuable source of resources (Serna-García et al., 2020; Song et al., 2018). While the A^{2}MBR system presents a promising multipurpose technology, demonstrating the practical feasibility of the A^{2}MBR could pave the way for its wider adoption as an effective alternative for sustainable wastewater treatment and resource recovery.

To ensure the successful implementation of advanced treatment technologies for wastewater reuse, a comprehensive sustainability assessment is essential (Dingemans et al., 2020). Such assessments should consider not just technical factors but also environmental, economic, and social criteria over both the short- and long-term. Through evaluating projects along all dimensions of sustainability, planners understand and mitigate risks as well as realize the full range of benefits from water reuse (Rodríguez-Castillo et al., 2023). Essentially, every community needs to carry out its own sustainability review to determine if and how wastewater recycling can be viably and responsibly achieved given local conditions and constraints (Halla et al., 2022). Evaluating economic, environmental, and social consequences is critical to fully understanding a project's long-term impact.

There are several common frameworks for carrying out sustainability assessments. While several studies have evaluated the sustainability and applicability of membrane-based treatments and their variations, the focus has primarily been on the environmental impacts throughout their life cycle. One study conducted a Life Cycle Assessment (LCA) to compare AnMBR-based domestic wastewater treatment trains with conventional activated sludge (CAS) treatment (Harclerode et al., 2020). Their findings concluded that the combination of primary sedimentation with anaerobic digestion, alternative processes for dissolved methane removal, and biological sulfide removal has the potential to render AnMBR treatment of domestic wastewater more energy-efficient and sustainable than conventional aerobic treatment. Another study has examined the environmental impact of AnMBR demonstration plants treating urban wastewater under varying operational conditions (Jiménez-Benítez et al., 2020). The study revealed that reactor mixing, and membrane scouring are the major energy-consuming processes and that the net energy balance can be significantly improved by increasing the BOD load in the influent. While LCA studies on different configurations of MBRs offer valuable insights for planning, designing, and improving wastewater management, policies, treatment infrastructure, collection, and reuse systems, a comprehensive sustainability assessment, particularly considering broader aspects beyond the technical and environmental realms, is yet to be conducted (Starkl et al., 2022). The same is true for the further development of A^{2}MBR, which is the focus of this study.

The Integrative Concept of Sustainable Development (ICoS) emerged from a rigorous interdisciplinary process to translate sustainable development principles into actionable guidelines. It encompasses three overarching sustainability goals and 25 specific sustainability rules. ICoS emphasizes the importance of developing indicators systematically and coherently, bridging the gap between theoretical concepts and practical implementation in the realm of sustainable development (Kopfmüller and Barton, 2012). Compared to other frameworks, ICoS aims at decoding the constituent elements of sustainable development, as they were outlined by the World Commission on Environment and Development (WCED) (WCED, 1987) and the following Rio Declaration, into three integrative sustainability goals. These integrative sustainability goals identify the impact of technologies or systems on the individual living conditions (goal 1), on entire economies (goal 2), and on societal prospects (goal 3), considering always more than one dimension.

Several studies have been conducted to evaluate the use of ICoS in the sanitation sector, including a framework for the management of municipal solid waste in Bello Horizonte, Brazil (Fuss et al., 2018), the sustainability performance of the water and sanitation services in Santiago, Chile (Simon and Lehn, 2012), and their application to different water infrastructure systems in Chillán, Chile (Steiner et al., 2018). The studies detected sustainability deficits (e.g., lack of controlling capacity of the regulatory agency, lack of consumers' participation, lack of long-term perspective for the planning of water resources to cope with the challenges of climate change) and presented possibilities for actions. The Integrative Concept of Sustainable Development (ICoS) framework has demonstrated its effectiveness in evaluating the sustainability of water and sanitation services in Chile through prior studies. However, its application to assess the sustainability of novel water reuse technologies, such as the A^{2}MBR system, remains unexplored in the Chilean context. This study aims to bridge this gap by employing the ICoS framework to conduct a comprehensive sustainability assessment of the A^{2}MBR system, considering its environmental, economic, and societal impacts across the three integrative sustainability goals outlined by the framework.

3. Methods

3.1. Status quo

The Botanical Gardens of Viña del Mar (BGVM), managed by the National Botanical Gardens Foundation, is located in Chile's Valparaiso region. The BGVM spans 395 ha, with 33 ha accessible to its >400,000 annual visitors (Fundación JBN, 2022). While promoting environmental education, the BGVM plays a crucial role in protecting 779 endemic species, many of which are threatened in their natural habitats.

The BGVM is situated along the El Olivar Creek watershed, a tributary to the Marga-Marga River that flows through Viña del Mar city and out to the ocean (Fig. 1). The creek regulates the gardens' water system while providing shelter for various aquatic life. Water from El Olivar is pumped into a storage tank to meet the garden's demands, including irrigation, toilet flushing, and other park services.

Irrigation is the primary water-consuming activity, with an average of 1 L/s per hectare of grounds and 3 L/s per 32 ha of forest. The BGVM relies on the local sanitary authority for potable needs, with an average monthly consumption of 200 m^3 used in administration buildings and handwashing stations throughout the gardens. As the stream flow decreases during the summer months, occasionally, there is an additional potable demand to cover irrigation needs. As for wastewater, there are 3 elements: the submarine outfall, the Quillota Wastewater Treatment Plant (QWTP, a conventional activated sludge plant serving the towns of Quillota, Limache, La Cruz, Hijuelas, Artificio, and La Calera), and the local BGVM system. The 2-North or 2 N submarine outfall carries primary treated wastewater from upstream nearby cities. This serves the towns of Villa Alemana, Quilpué, Reñaca and part of Viña del Mar. It is independent of the Botanical Garden (BGVM) and crosses the BGVM as an underground sewage pipeline. The BGVM is not connected to this pipeline and wastewater generated onsite is collected in septic tanks. BGVM wastewater is trucked 46 km to the QWTP for treatment.

3.2. Alternative system: A^2MBR

A potential alternative to offsite effluent disposal could use A^2MBR treating local wastewater and a fraction of the primary sewage conveyed by the marine discharge pipeline (design flow of 1000 m^3/d or 11,57 L/s) (Fig. 2). The treatment train comprises primary sedimentation and equalization tanks, A^2MBR reactors, and a disinfection unit. Excess algal biomass and sludge are co-digested to increase methane gas production. The biogas is used in a Combined Heat and Power plant (CHP) to cover the plant's power and heat needs. Effluent quality meets local regulations and guidelines for treated wastewater reuse in irrigation (Fig. 2). Treated effluent is stored for distribution based on BGVM's needs (irrigation and toilet flushing). Mass balances for sludge, nutrients, and chemical oxygen demand (COD) are based on the experimental results of an A^2MBR pilot plant (Prieto, 2011). Drying beds are used to manage sludge, with resulting biosolids applied on-site for soil amendment. Technical specifications for the treatment train are provided in Supplementary Information (SI).

Fig. 3 presents the material and energy flow for the BGVM, where the current water-energy flows are shown in blue (*status quo)*, while the proposed alternative with an A^2MBR is shown in green. For the *status quo*, there are four inputs of water: 1) El Olivar stream, which supplies water for ground irrigation, latrines, and recreational uses; 2) rainwater that is transported through El Olivar as surface runoff; 3) potable water that is used for drinking purposes, hand washing, and administrative building needs; and 4) groundwater (black dotted arrow in Fig. 3), which is currently not used due to the high cost of operation, as the water must be pumped 30 m from the groundwater level. Flows 1) and 2) combine into the lower El Olivar Creek and continue into the Marga-Marga Creek, which crosses the city of Viña del Mar and discharges into the sea. Other relevant inputs include the energy (i.e., electricity) required for space and water heating and fuel required by the trucks providing latrine cleaning services.

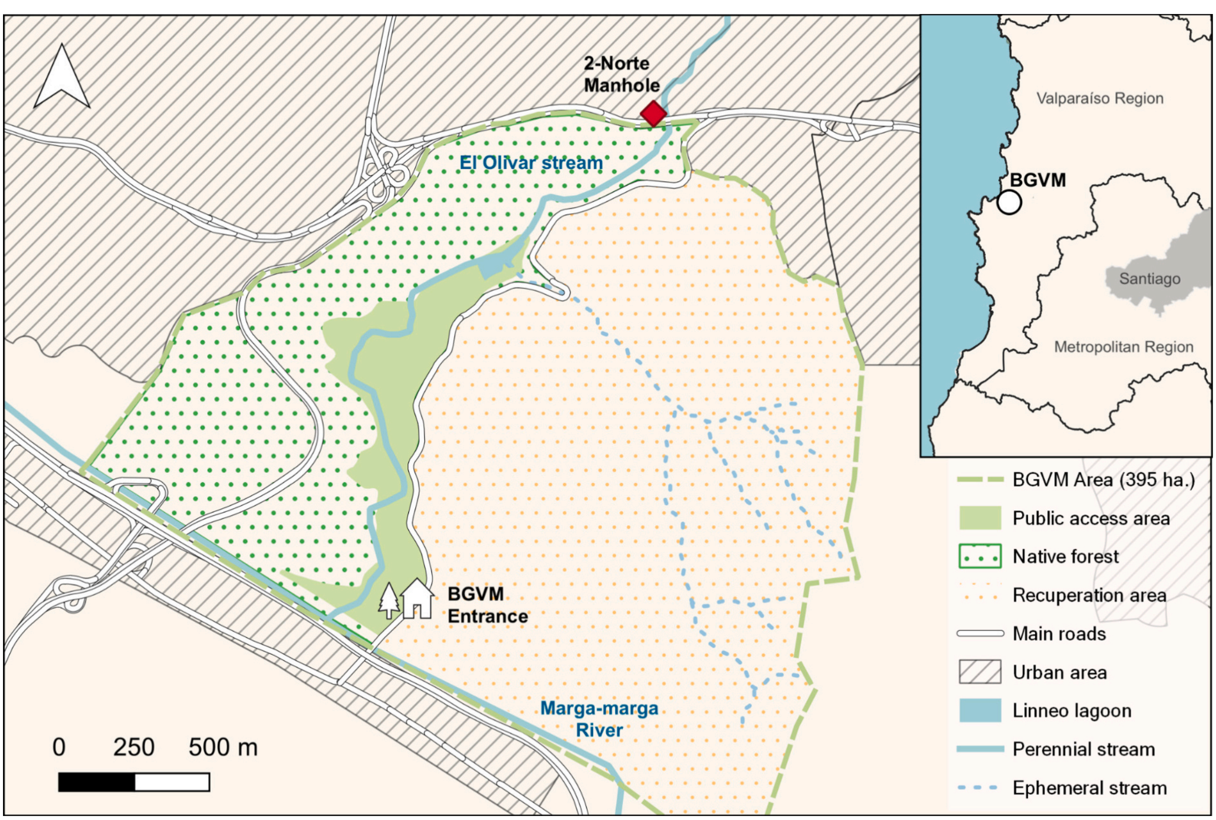

Fig. 1. Map of the Botanical Gardens of Viña del Mar (BGVM). The main stormwater catchment area flows into the Linneo Lagoon. The perennial stream El Olivar feeds the Linneo Lagoon and then flows into the Marga-Marga Stream.

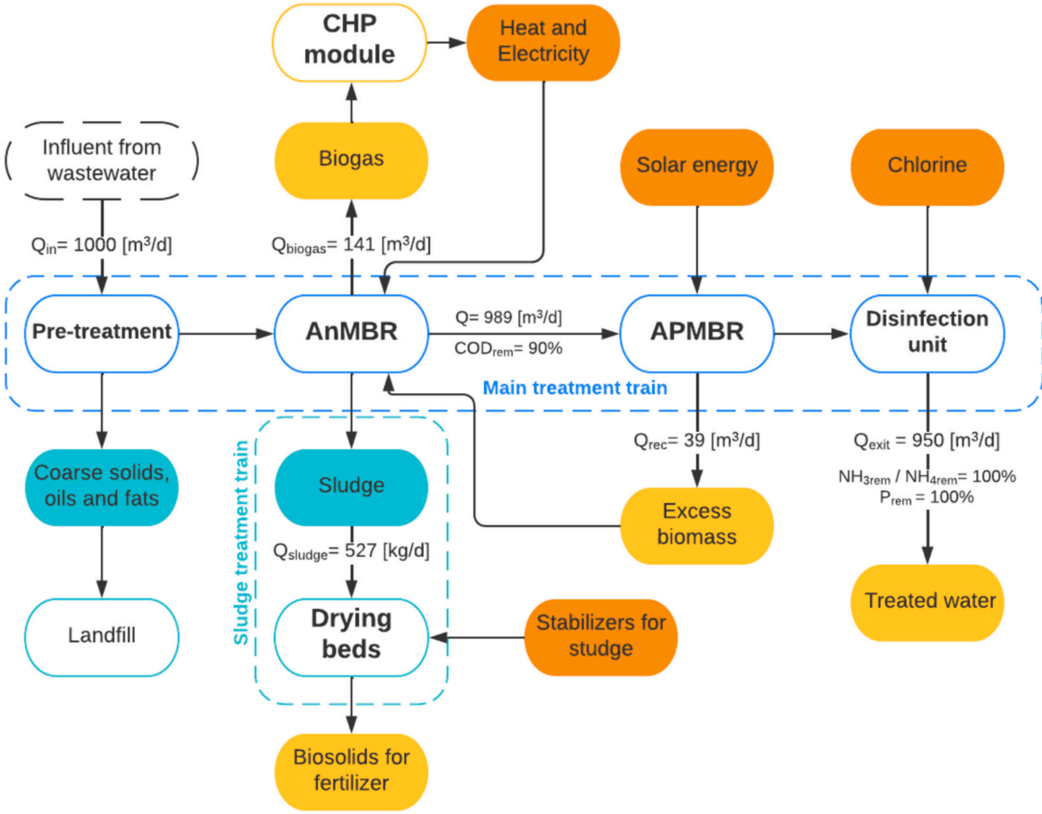

Fig. 2. Schematic of the Anaerobic and Algal Membrane Bioreactor (A^{2}MBR) plant at Botanical Gardens of Viña del Mar (BGVM). CHP: Combined Heat and Power.

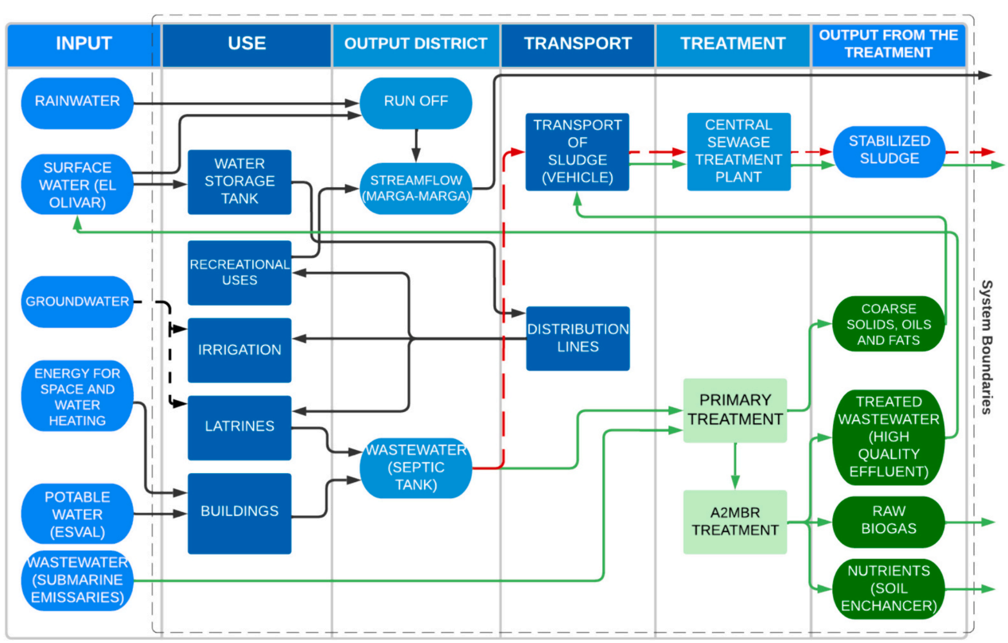

Fig. 3. Baseline energy and material flow diagram for the Botanical Gardens of Viña del Mar (BGVM).

The alternative system scenario includes onsite wastewater treatment by the A^{2}MBR to generate a high-quality effluent for irrigation and recreational purposes. The red dotted lines indicate the flows to be substituted by the new technology. The A^{2}MBR will treat the wastewater from the submarine emissary and latrines, eliminating the latrine-waste collection. The contribution of the latrine's flow is negligible compared to the emissary's. The combined influent characteristics for the status quo are COD = 396 [mg/L], BOD = 220 [mg/L], TKN = 51,32 [mg/L], TP = 8,24 [mg/L], TSS = 177,22 [mg/L]. Nutrients are recovered within the system boundaries due to the onsite sludge management.

3.3. *Indicators for sustainability assessment based on the ICoS framework*

Based on the three constitutional principles of Sustainability, derived among others from the Brundtland Report (World Commission, 1987), the ICoS identified three goals: a) Securing human existence, b) Maintaining society's productive capital, and c) Preserving society's options for development and action (Kopfmüller et al., 2001). In a previous study (Rodríguez-Castillo et al., 2023), we identified the respective rules and indicators that fulfilled the objective of characterizing the advantages, disadvantages, and challenges of implementing the A^2MBR technology at BGVM for water reuse purposes. Indicators were formulated based on literature research, data availability, and local expert interviews. We selected 19 indicators for the present study (Fig. 4) based on data availability and discarded others due to the difficulty of accessing information given the local context. Details on input values are provided in SI.

In brief, two rules were selected for the goal of "Securing human existence": 1 - *Protecting human health* and 2 - *Ensuring the satisfaction of basic needs.* For rule 1, there are three indicators related to the removal of viruses, bacteria, and estradiol (Indicators 1a to 1c, Fig. 4). As there is no available data on the current QWTP and A^2MBR technology, the value of some indicators is based on existing literature. The following data for indicators was obtained from literature: Coliphages removal in Conventional Wastewater Treatment Plants (CWTPs) (Flannery et al., 2013; Plummer et al., 2014; Vijayavel et al., 2010) and in MBRS (Chaudhry et al., 2015; De Luca et al., 2013; Purnell et al., 2016); Estradiol removal in CWTP (Nazari and Suja, 2016), aerobic MBRs (Xiao et al., 2019; Zhou et al., 2011), anaerobic MBRs (Aziz and Ojumu, 2020; Wu et al., 2011), and algal MBRs (Ruksrithong and Phattarapattamawong, 2019). As water recovery for irrigation is relevant in the assessment, there is an indicator for the provision of urban blue-green spaces with treated wastewater (Ind. 1d). This indicator is calculated as the generation of treated wastewater minus the water demand for sanitation. For the second rule, there are indicators for the presence of nutrients (Total Nitrogen and Phosphorus) in the effluent (Ind. 2a) and biosolids (Ind. 2b) of the treatment, as both will be "discharged" back to the environment. Two indicators related to water and energy provision were included (Ind. 2c to 2d), as revalorization of the treatment products is the main attribute of the A^2MBR. All these indicators will be calculated using mass balances based on the quality of the influent and the operational conditions of the A^2MBR.

Indicators for the goal of "Maintaining society's productive potential" are required to evaluate the sustainable use of current resources to support future demands. Four ICoS rules were identified as relevant for the study case: *3-Sustainable use of renewable resources, 4-Sustainable use of non-renewable resources, 5-Sustainable use of the environment as a sink,* and *6-Sustainable development of man-made, human and knowledge capital.* An indicator to quantify the drinking water requirements (Ind. 3a) is assigned to the first rule, as potable water requirements in the current system are expected to change with the implementation of the A^2MBR. For the rule "*Sustainable use of non-renewable resources*" indicators such as net demand for fossil fuels (Ind. 4a) and net demand for nutrients by the BGVM (Ind. 4b) are established as the implementation of the A^2MBR would change the dynamics of nutrients and energy demand in the system (by means of transport or power generation). The indicators will be calculated from data from the BGVM and mass balances.

As for the rule "*Sustainable use of the environment as a sink*", an indicator that assesses the solid waste generation by the system is included (Ind. 5a). Commonly used environmental indicators such as Global warming potential (GWP) (Ind. 5b), Eutrophication potential (EP) in water bodies (Ind. 5c), and Acidification potential (AP) (Ind. 5d) are also included and calculated using a Life Cycle Assessment (LCA), which corresponds to three impact categories of ReCiPe2016 (Huijbregts et al.,

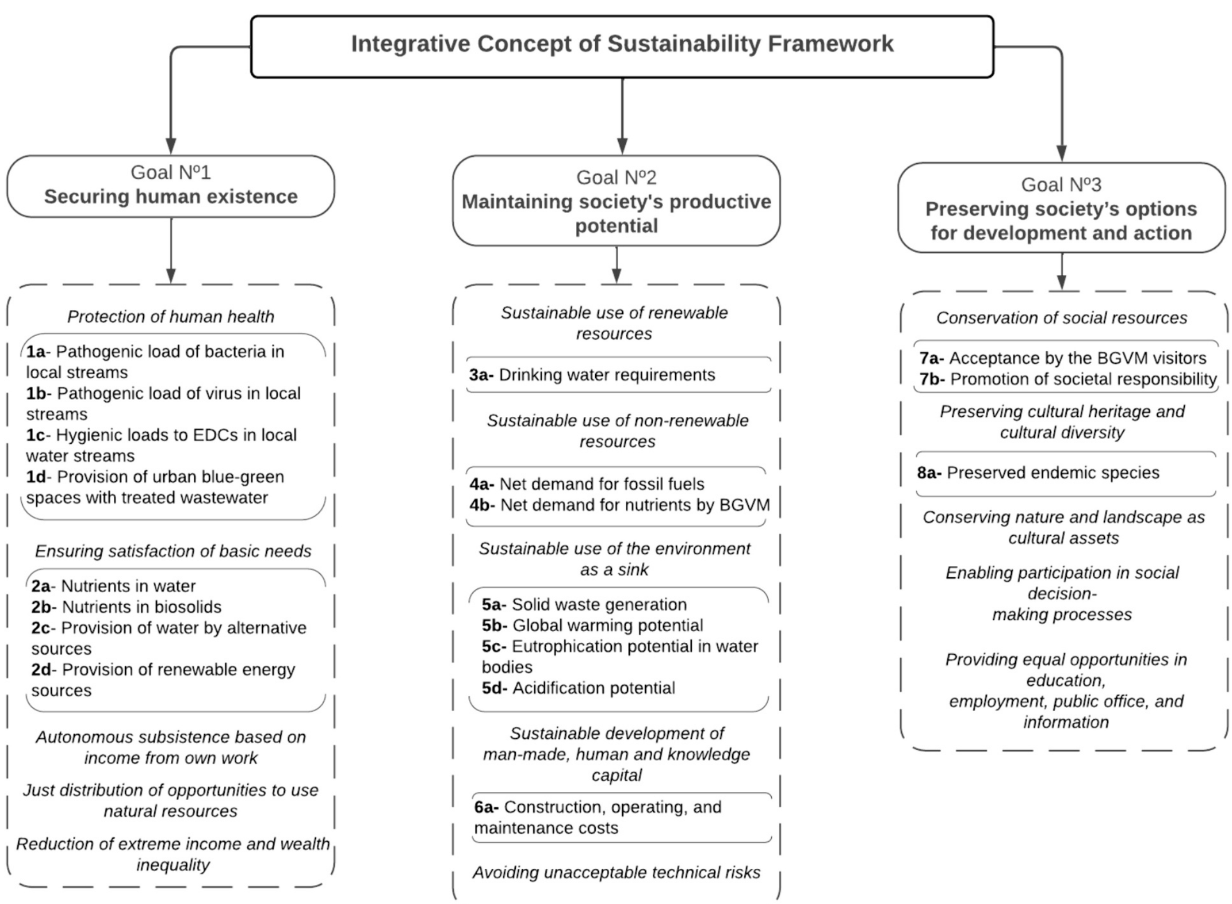

Fig. 4. Indicators selected for the study.

2017).

Lastly, for the rule *"Sustainable development of man-made, human and knowledge capital,"* Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) values are used for Ind. 6a - *construction*, operation, and maintenance. Historical cost benchmarks are unavailable as the A^2MBR is yet to be constructed. Thus, CAPEX values are estimated based on the direct and indirect costs in a multipurpose plant, according to Peters et al. (2002). A sensitivity analysis was done for each of the components of the direct and indirect costs, being 1) Equipment, 2) Service Facilities, 3) Instrumentation and Controls, 4) Engineering and Supervision, and 5) Construction (Details are provided in SI). Additional operational costs (e.g., labor) were obtained from experts in the Chilean wastewater industry (private communication). For the A^2MBR, five main equipment components were considered: a Pre-Treatment unit, an Anaerobic reactor, a Photoalgal reactor, ultrafiltration membranes, and disinfection modules. Drying beds and solar Panels were considered in the total costs. The A^2MBR operational and maintenance (O&M) costs include salaries for dedicated personnel, lab services, and the costs of materials such as Sodium hydroxide (NaOH), Sodium hydroxide (HCl), Calcium oxide (CaO), and chlorine for membrane cleaning and pH/alkalinity control. Membrane replacement is considered every ten years. The design operation lifetime is 20 years. Costs also include constructing and maintaining solar panels with an installed capacity of 400 kW, producing around 683,500 kWh of electricity per year. The solar panels' energy would completely cover the energy demands of the new treatment system. The costs for the *status quo* were disclosed by the sanitary company (ESVAL, 2023).

Finally, there are three indicators for the goal of "Preserving society's options for development and action". Selected rules for the study are *7-Conservation of social resources* and *8-Conservation of the cultural function of nature*. Indicators are the acceptance of the use of recycled wastewater in the BGVM by its visitors (Ind. 7a), promotion of societal responsibility (Ind. 7b), and preserved endemic species (Ind. 8a). All three indicators will be discussed qualitatively based on available studies done in Chile.

3.4. Life cycle assessment (LCA)

The main constituents of an LCA are defined by ISO 14040 and ISO 14044 standards (International Organization for Standardization (ISO), 2006). The functional unit for comparing the impacts of the two scenarios (*Status quo* vs A^2MBR alternative) is 1 m^3 of treated wastewater. The assessment uses inventory data from the Ecoinvent 3.8 database (Wernet et al., 2016), mass balances, pertinent literature data, and specific information from the BGVM. All Life Cycle Inventory (LCI) unit processes were created using the open-source LCA software OpenLCA (version 2.0.3) developed by GreenDelta GmbH (https://www.openlca.org/).

The ReCiPe Life Cycle Impact Assessment (LCIA) method was employed with Midpoint (H) (Huijbregts et al., 2017). The LCIA considers the construction and operation of the A^2MBR system (spanning 20 years), along with material, reagents, and sludge transport (with an average distance of 20 km for construction) within the system boundary. However, demolition phases involving materials disposal and recycling were excluded from the analysis. The lifespan of membrane modules, sensors, and pumps was estimated based on manufacturers' specifications. Nutrient reuse in stabilized sludge for soil enhancement was accounted for as a credit without resorting to landfill or incineration. Biogas methane was considered for energy utilization, but the capture of dissolved methane by degassing membranes was not included. All the electricity demand is covered by solar panels.

For the A^2MBR system, the LCI was developed based on the MBR plant's existing literature, including energy demand of equipment, infrastructure materials, earthworks, pretreatment, and chlorination (Cashman et al., 2016). Impacts from CHP were calculated for a microturbine with efficiency of 27 % for electricity (USEPA, 2015) and 34 % for heat (Metcalf and Eddy, 2014). A^2MBR outputs to the environment (i.e., treated effluent, usable sludge, and biogas) are considered an "avoided burden" for LCA purposes. Market input providers were obtained from the Ecoinvent database (Global and Rest of the World or Global datasets). The analysis includes shipping construction materials from abroad, internal distribution pipelines, and solar panel installation.

For the *status quo*, LCI for the QWTP was developed using the LCI developed for an extended aeration treatment for a small facility (1123 m^3/d) in Latin America (Hernández, 2016). Emissions derived from the transport of the sludge from the BGVM to the QWTP are also accounted for. Emissions derived from energy demands for the QWTP are considered electricity production based on the Chilean electricity mix, which is predominantly fossil-based (62 %).

4. Results and discussion

4.1. Indicators for Goal 1 "Securing human existence"

Table 1 summarizes the selected indicators for Goal 1. The primary concern for wastewater reuse in urban green spaces and recreational environments is the presence of pathogens. The indicator "Pathogenic load of bacteria in local streams" (Ind. 1a) shows average values of *E. coli* in the effluent treated by MBRs (details in SI). Comparing the QWTP's and A^2MBR's treatments, literature shows that membrane rejection is superior to gravitational settling and log-removal of *E. coli* is approximately 3 orders of magnitude higher in MBRs than in a conventional activated sludge process (CASP) (Chen et al., 2020). Thus, the removal of *E. coli* should be higher as the wastewater undergoes two stages of membrane filtration in the A^2MBR treatment and a final chlorine dosage of 1.8 mg/L for disinfection. As the literature suggests that *E. coli* can tolerate up to 0.5 mg/L chlorine concentration before inactivation (Owoseni and Okoh, 2017), the removal and inactivation of *E. coli* are assumed to be high in the A^2MBR. According to existing guidelines, inactivation values higher than 4 log-removal are considered safe for recreational waters (USEPA, 2012; European Parliament, 2006) and

Table 1
Indicators for Goal 1.

Rule	Indicator	Unit	Value (A^2MBR)	Value (Status Quo)
1 - Protection of human health	1a - Pathogenic load of bacteria in local streams	Removal of *E. coli* [log-removal]	>6.5	6.5
	1b - Pathogenic load of virus in local streams	Removal of F-specific Coliphage [log-removal]	5.1	2.8
	1c - Hygienic loads of Endocrine-Disrupting Compounds (EDCs) in local water streams	Removal of Estradiol [%]	97	92
	1d - Provision of urban blue-green spaces with treated wastewater	m^3/y of available treated wastewater	308,178	0
2- Ensuring satisfaction of basic needs	2a - Nutrients in water	kg/y of P and N in effluent	P: 0 N: 180	P: 1650 N: 11,350
	2b - Nutrients in biosolids	kg/y of P and N in solids	P: 3010 N: 12,800	P: 830 N: 41,500
	2c - Provision of water by alternative sources	m^3/y	346,750	0
	2d - Provision of renewable energy sources	MWh /y	316	0

even for reusing treated wastewater (Texas Commission on Environmental Quality, 2009).

Pathogenic load of virus in local streams (Ind. 1b) is measured as the log-removal of F-specific Coliphage. In practice, full-scale MBRs demonstrate a 3–6 log-removal of the tested viruses, much higher than CASP (1–3 log removal) (Xiao et al., 2019). Specifically, F-specific coliphages show an average of 5.1 log-removal in different full-scale MBR studies (Chaudhry et al., 2015; Purnell et al., 2015; Purnell et al., 2016). According to the United States Environmental Protection Agency (USEPA) National Primary Drinking Water Standards, enteric viruses must be removed or inactivated by 4 log-removal (99.99 %) during water treatment from surface waters (USEPA, 2023). Regarding regulations for reclaimed waters in other countries, the A^2MBR system meets French regulations requiring a minimum of 4 log-removal of pathogens for direct reuse (France, 2014). However, it does not achieve the more stringent ≥6-log European Union (EU) standard for agricultural reuse (European Parliament, 2020). A Chilean regulatory framework for virus removal in reclaimed water is yet to be developed.

Hygienic loads of Endocrine-Disrupting Compounds (EDCs) in local water streams (Ind. 1c) are estimated based on literature data on MBR operation. The primary estradiol removal mechanism of the system is the ultrafiltration membrane, which shows removals above 95 % (Zhou et al., 2011; Wu et al., 2011; Aziz and Ojumu, 2020). Other removal mechanisms include biodegradation and adsorption. AnMBRs coupled with aerobic treatments are effective (97 %) in removing 17-beta-estradiol (E2) (Wu et al., 2011). One study found that the microalgae strain *C. vulgaris* removes 99 % of E2, with biodegradation followed by adsorption being the primary removal mechanism (Ruksrithong and Phattarapattamawong, 2019). CASP removal of E2 varies from 85 % to 99 %, depending on treatment configuration and operational conditions (Nazari and Suja, 2016). Since the A^2MBR couples and AnMBR and Algal-PMBR, the alternative treatment could potentially provide better removal of viruses vs QWTP. However, adsorbed estradiol into the sludge must be considered for all the treatments discussed.

As droughts become more frequent in the area, using reclaimed wastewater to irrigate green spaces can help mitigate the limited water supply in the BGVM. The current system does not reuse any water. The proposed A^2MBR system would provide 346,750 m^3/year of additional water (Ind. 2a) to irrigate existing forests and meadows (56,160 m^3/year) and recover 250 ha of native forest (263,250 m^3/year). This accounts for 90 % of the total available treated water (308,178 m^3/year), reported in *Provision of urban blue-green spaces with treated wastewater* (Ind. 1d). Details on mass balance calculations are provided in SI. Restoring native forests improves the local water budget as native species may adapt more to water stress (Jones et al., 2022). For the BGVM, providing additional green spaces also benefits its economic activity as a tourist hotspot in a densely urbanized area.

Considering the load of nutrients in the treated wastewater (Ind. 2a), both the QWTP and A^2MBR comply with Chilean regulations for effluent discharge on surface waters (i.e., DS90) (Congreso Nacional de Chile, 2001). However, QWTP's effluent does not contribute as an alternative water source to the BGVM. Compared to the current system, the results show higher phosphorus and nitrogen removal in the A^2MBR (>99 %). Although the A^2MBR effluent concentrations of total kjeldahl nitrogen (0.5 mg/L) and total phosphorus (<0.01 mg/L) cannot be a source of nutrients alone, the treated effluent provides a sustainable source of water for various BGVM's irrigation demands. The advantage of applying the new system depends on the final use of the treated water.

Recovery of nutrients in biosolids is accounted for in Ind. 2b. In comparison to the QWTP in the *status quo*, the A^2MBR treats a considerably smaller amount of water, and all its biosolids are used for soil amendment in the BGVM. On the contrary, there is more phosphorous recovery in the A^2MBR system due to algal growth (P-uptake) and further concentration in the digested biosolids. The benefits associated with the biosolids as a soil amendment are to be measured since the bioavailability of these nutrients can vary depending on the source and composition of the sludge, drying methods, and soil conditions (Onchoke and Fateru, 2021).

Ind. 2d accounts for on-site energy recovery via CHP. Heat production from biogas meets approximately 14 % of the A^2MBR's energy demands (633,492 MJ/y), covering the heating demands for the anaerobic reactor. Electricity production is 503,067 MJ/y (140 MWh/y), adding to the current supply from solar panels.

4.2. Indicators for Goal 2 "Maintaining society's productive potential"

Indicators for Goal 2 are shown in Table 2. Effluent from the A^2MBR would decrease the demand for potable water in half (Ind. 3a) by displacing its use in latrines. The change in the indicator value also considers a decrease in potable water used for irrigation at certain times of the year. Using reused wastewater can also reduce the BGVM's reliance on centralized water treatment plants and potentially reduce current costs associated with potable water consumption. Amidst the ongoing drought in Chile, the alternative system can help conserve potable water and reduce stress on natural water resources.

The A^2MBR reduces the demand for fossil fuels per m^3 of treated wastewater (Ind. 4a); however, this demand significantly increases when accounting for the total amount of water treated annually (i.e., kg oileq/y). The primary source of emissions for the *status quo* is associated with land transportation of the sludge from the BGVM to the QWTP. Further, the QWTP relies on the national energy mix (68 % fossil fuels), accounting for 88 % of the system's demand. Since the alternative system provides on-site sludge management, no fossil fuel is used for sludge transportation.

For Ind. 4b, the annual demand for nutrients in the BGVM includes 150 kg of commercial fertilizer with a composition of 15 % of total Nitrogen (N) and 8 % of Phosphorus (P). According to the mass balance of nutrients in the A^2MBR (cf. SI), the system would produce 227 tons of stabilized and dried sludge annually as a soil enhancer, with a content of 6 % of N and 1 % of P per kg. Even though the concentration of N and P in A^2MBR's biosolids is lower than in commercial fertilizers, they are a free source of nutrients readily available for onsite uses, including landscape maintenance and recuperation, offering a sustainable

Table 2
Indicators for Goal 2.

Rule	Indicator	Unit	Value (A^2MBR)	Value (Status Quo)
3 - Sustainable use of renewable resources	3a - Drinking water requirements	m^3/y	60	180
4 - Sustainable use of non-renewable resources	4a - Net demand for fossil fuels	kg oil_{eq} /m^3 kg oil_{eq} /y	0.12 44×10^3	5.8 696
	4b - Net demand for nutrients by BGVM	kg/y of P and N	P: 1490 N: 6440	P: 10 N: 20
5 - Sustainable use of the environment as a sink	5a - Solid waste generation	kg_{waste}/y	19,300	47,500
	5b - Global warming potential	kg CO_{2eq} /m^3 kg CO_{2eq} /y	0.22 80×10^3	2.5 300
	5c - Eutrophication potential in water bodies	kg P_{eq} /m^3 kg P_{eq} /y	1.8×10^{3} 657	8.1×10^{3} 0.972
	5d - Acidification potential	kg SO_{2eq} /m^3 kg SO_{2eq} /y	8.6×10^{4} 313.9	3.3×10^{2} 4.02
6 - Sustainable development of man-made, human and knowledge capital	6a - Construction, operating, and maintenance costs	\$USD/m^3	1.72–2.46	3.61

alternative to conventional fertilizers and reducing waste.

Ind. 5a refers to any solid waste that might be disposed of in landfills. QWTP reports 47 tons per year of solid waste sent to landfills per 365,000 m^3/year of treated wastewater, where coarse solids from preliminary treatment are significant (SNIFA, 2021). The A^2MBR receives preliminary treated water from the submarine emissary; thus, solid waste to landfills is due to filtering materials and membrane modules that must be replaced every ten years (Judd, 2022), in addition to 10 % of dried sludge produced. The A^2MBR generates almost 60 % less solid waste than the *status quo,* producing fewer biosolids to be used as soil enhancers.

The results of the LCA suggest a reduction in indicator 5b (GWP), 5c (EP), and 5d (AP) per m3 of treated wastewater for the new system. The transportation of the wastewater to the QWTP in the *status quo* represents 86 % of the CO_{2eq} emissions (2.5 kg CO_{2eq}/m^3). By eliminating land transportation of wastewater, providing onsite treatment with the A^2MBR, and using solar panels, potential environmental impacts in the BGVM are reduced by more than half. Even though A^2MBR's energy consumption is higher, it is covered by renewables that reduce greenhouse gas emissions. When considering the wastewater treated annually by the A^2MBR system, the GWP impact significantly increases. Yet AP and EP decrease under the new system by treating wastewater onsite that otherwise would have been discharged to the environment.

Ultimately, costs, i.e., the needed financial resources to install and operate innovative wastewater treatment systems, are among the most critical aspects of implementing the A^2MBR. Comparing both systems, the costs of m^3 of treated wastewater by the A^2MBR are lower than the *status quo*, varying between 16.6 % and 41.7 % (see Table 2). For calculating the capital investment costs, the cost components' share varied following Peters et al. (2002). The current system's main cost driver is the QWTP treatment, which accounts for 80 % of the total costs. The remaining 20 % corresponds to the transportation to the QWTP. Values include operating as well as investment costs. One should note that the high costs of the current system are economically feasible for the BGVM as the volumes of wastewater are small and thus, the entire financial burden. However, the alternative system would reduce them considerably since the wastewater will be treated on-site.

For the alternative system, the share of the CAPEX varies between 38 % and 54 % of the total costs, depending on the composition of the investment costs. Equipment costs are the most influential share of the CAPEX, ranging between 15 % and 40 % (Peters et al., 2002). The OPEX varies between 46 % and 62 % of the total costs, whereas replacement parts constitute 37 % of the OPEX. The alternative system's main cost driver is wastewater collection from households to the 2 N S.E. (50 % of the total cost) (cf. SI).

4.3. Indicators for Goal 3 "Preserving society's options for development and action"

Although there is no specific information regarding the public acceptance of treated wastewater from the A^2MBR system, there is evidence that reusing wastewater is not alien to citizens in Valparaiso and other regions of Chile (ANDESS, 2023; Vera-Puerto et al., 2022). According to an existing citizen survey, treated wastewater is perceived as an acceptable alternative for irrigation purposes and restoring native forests (PAR Explora, 2020). When 630 respondents were asked about the suitable uses for the treated wastewater, 79 % of the people considered the irrigation of gardens and green areas with public access, and 78 % also considered the irrigation of reforested species and wetlands. Other uses include toilet flushing (64 %) and industrial processes (54 %) (PAR Explora, 2020). While precise knowledge of the treatment processes varies between regions in Chile, confidence in the quality of treated water exceeds 50 % (Segura et al., 2018).

Regarding promoting societal responsibility (Ind. 7b), it is unclear whether applying the A^2MBR system would show changes in the indicator. In the same survey, when asked about what they believed to be the main water-related challenge of the country, The primary response was to conserve natural water sources, protect ecosystems, and ensure access to drinking water for human consumption (32 % each), followed by improving water-related laws and institutions (20 %). Only 10 % of the respondents pointed to water efficiency and education on the correct water use.

Lastly, providing a habitat for several endemic species is part of the BGVM's mission. For example, the Linneo Lagoon is the habitat of 50 species of birds, some of them difficult to observe in nature (Calderón-Carmona et al., 2016). The BGVM continuously monitors this information. Changes in endemic species can inform Ind. 8a (Preserved endemic species). Despite no association between biodiversity and well-being, the blue-green spaces promoted by the A^2MBR system could be essential for supporting different bird communities (Threlfall et al., 2017).

4.4. A holistic discussion of the A^2MBR system

Fig. 5 shows the improvement of some of the indicators in ICoS Goals N°1 and N°2 according to a best-value target. For Goal N°1, almost all indicators of the new system improved over the *status quo* values. The A^2MBR system improves indicators associated with viruses, bacteria, and EDCs that threaten human health more effectively than the conventional treatment in the *status quo*. The A^2MBR system provides further essential services, i.e., the provision of water for a facility that demands copious amounts of water for functioning, as well as the additional nutrients for the well-being of the vegetation and the recovery of soil and land. Even though Ind. 2b shows a negative value compared to the *status quo*; the nitrogen recovery in the A^2MBR's biosolids will be used in the BGVM.

Regarding Goal 2, the A^2MBR system shows considerable relief of the environment as a supplier of resources but also as a sink. The estimated costs of on-site treatment seemed competitive compared to existing alternatives to water supply (i.e., up to 2 USD/m^3 for desalination) while reducing the net demand for fossil fuels due to waste transportation (Vicuña et al., 2022). There is a trade-off between increased water availability and higher GWP. Additional provisions of water in the BGVM result in more urban blue-green spaces. Environmentally, urban green zones aid in mitigating drought effects by conserving water and fostering biodiversity. Additionally, these spaces act as habitats for various plant and animal species, including those well-suited to drought conditions, thereby upholding biodiversity within urban environments (Threlfall et al., 2017).

Despite not directly quantifying the indicators proposed for Goal 3, existing literature provides some insights into their outcomes. First, 30 % of wastewater currently discharged into the sea is expected to be available for reuse in Chile by 2030 (SiSS, 2023). There is evidence of acceptance of treated wastewater as an alternative source in the face of the current drought (Vera-Puerto et al., 2022). However, it is essential to have a case-specific survey for a more complete analysis since acceptance of the new system may vary between age groups and between occasional and frequent visitors. Furthermore, communities near the garden may complain about the new system due to potential odors and noise (Arora, 2020). Although some efforts have been done for the standardization of sustainability assessments applied to decentralized wastewater treatment solutions (Cid et al., 2022; Starkl et al., 2015), the subjectivity of qualitative indicators remain a challenge in sustainability assessments. For the BGVM, surveys of visitors and neighbors are needed to corroborate public acceptance.

5. Conclusions

This study analyzed the sustainability of implementing the A^2MBR as an alternative wastewater treatment system in the BGVM. Key findings emerged from this study: First, the A^2MBR system enhanced water quality and availability in the water-scarce BGVM area. By enabling direct reuse of the effluent, the A^2MBR can improve water supply

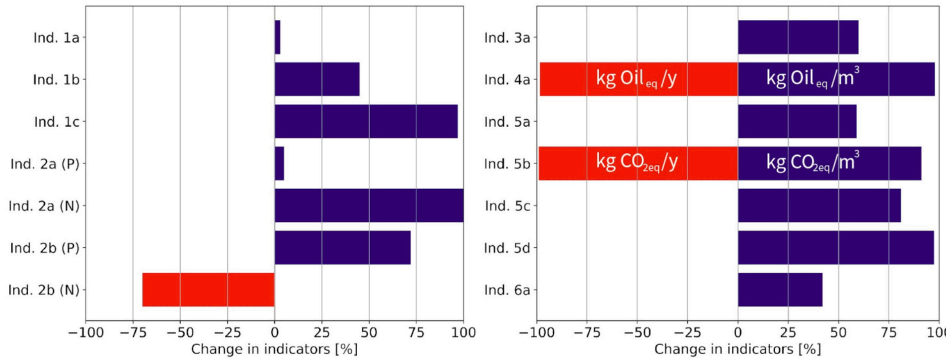

Fig. 5. Indicators for Goal 1 (left) and Goal 2 (right).

reliability while reducing the discharge of untreated effluents to sensitive water bodies. Our assessment found that the A^{2}MBR lowers environmental impacts compared to the existing system, mainly due to increased energy recovery as biogas, lower sludge production, and less fossil fuel use.

Finally, the economic analysis identified opportunities to reduce costs per cubic meter of treated effluent with the A^{2}MBR. This assessment demonstrates that transitioning to A^{2}MBR technology could provide a more sustainable approach to wastewater management in the BGVM watershed and similarly water-stressed regions. Pilot demonstrations and a long-term social assessment of the A^{2}MBR application will be vital to validate the sustainability benefits identified by our indicators. Although there are a few case-specific indicators, the applied methodology is transferable to other regions around the globe.

CRediT authorship contribution statement

Montserrat Rodríguez-Castillo: Writing – original draft, Writing – review & editing, Data curation, Investigation. **Naroa Balsebre:** Data curation, Formal analysis. **Vanessa Bolivar-Paypay:** Writing – review & editing. **Witold-Roger Poganietz:** Writing – review & editing. **Ana L. Prieto:** Funding acquisition, Methodology, Supervision, Writing – review & editing, 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.

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

The authors used Claude by Anthropic and Grammarly by Grammarly Inc. to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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