Chapter

Use of Saline Waste from a Desalination Plant under the Principles of the Circular Economy for the Sustainable Development of Rural Communities

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Abstract

In the region of Arica and Parinacota, Chile (South America), concerned about the environment, the use of brine from a reverse osmosis plant was considered as irrigation water, which is generally discharged into the sea, sewers, or nearby rivers. In this sense, the integrated management of this waste was studied under the 3 principles and 11 strategies of the circular economy, for which it will be used to produce halophilic fodder (*Atriplex nummularia*), supporting the sustainability of livestock farmers in the sector. As for the results, it was estimated that with 86,400 Lh-1 in 20 days of brine, 400 *A. nummularia* plants would be irrigated, with an energy consumption of 31,319 kWh per day, through a photovoltaic system. In addition, of the 11 strategies of the circular economy, this study complies with 9 of them. It is noteworthy that the combination of brackish water desalination technologies and solar energy to produce *A. nummularia* would avoid the production of 1.5 tons of CO_2. Finally, this study opens potential opportunities for future research, for the implementation of this type of project in rural communities, considering an optimization in the management of saline waste and water.

Keywords: circular economy, halophytes, brine, management of resources

1. Introduction

Climate change is already present and will continue to change, affecting societies and the environment [1]. This occurs directly through changes in hydrological systems that are influencing water availability, water quality, and extreme events, and indirectly through changes in water demand, which in turn can have impacts on energy production, social and environmental damages, food security and the economy, among others [2]. On the other hand, communities have increased pressure on

water resources, seeking new alternatives to mitigate the lack of this vital element. Among these alternatives is desalination technology, which is a solution to this problem [3], considering that the planet earth is 97.3% saltwater [4] and 2.5% freshwater [5]. However, in spite of being a solution that is becoming more and more common, this technology generates some environmental problems. On the one hand, it generates a product water or desalinated water that can be treated to be suitable for human consumption or irrigation, adding the necessary minerals, and on the other hand, a saline stream called brine that is generally disposed of in the sea, causing serious environmental problems [6]. It is estimated that for every 1 m^3 of desalinated water, between 0.3 and 1 m^3 of brine is generated [7]. Considering that the global product water capacity from seawater desalination plants as of 2020 was 9.72×10^9 m^3/d [4] and according to the above estimate, in the same year, there have been between 2.92×10^9 and 9.72×10^9 m^3 d^{-1} of brine. According to Ihsanullah 2021, reusing and recycling brine is presented as a good alternative to minimize the negative impacts it produces, being favorable on a small scale. However, he indicates that more work is needed to assess the feasibility of brine treatment in commercial or larger desalination plants [8].

On the other hand, today's economy is based on a circular model, which assumes that resources are abundant and that one must "take-make-consume-reuse." Therefore, given the large amount of brine produced today, reutilization is a matter of principle that is strongly linked to the circular economy [9]. In that sense, wastewater such as brine is a valuable water, energy, and material resource; therefore, it is essential to manage its use and final disposal, following strategies of reduction, reuse, recycling, recovery, restoration, and regeneration, among others of the circular economy [10]. In addition, it is worth noting that the idea of circular economy through business models that encourage reuse and recycling can be very relevant for arid regions [11], where water is a valuable resource for basic needs such as drinking and sanitation, or for irrigation.

The agricultural sector uses 70% of the world's water and is one of the most important sectors for human beings. According to the WHO, it is estimated that by the year 2050, the demand for food products will be approximately 70% higher than today, as a result of population growth [12]. On the other hand, FAO, in its reports "The State of Food and Agriculture," indicates that 1.2 million people live in agricultural areas with high levels of water stress and 520 millions of them live in rural areas [13]. In addition, special attention is paid to agri-food systems, where food-producing families engaged in small-scale agriculture are increasingly being put to the test due to the lack of water for irrigation [14]. These potential effects on agriculture are mainly due to climate change, which could lead to regions with increased salinization and desertification in arid areas of South American countries such as Chile and Brazil [15].

The Arica and Parinacota region is located in northern Chile and has arid characteristics. Although this region has available water resources such as the Lluta River or Camarones River, this water is limited and of poor quality due to high concentrations of arsenic, boron, and total dissolved solids (TDSs) [16] that exceed standards such as NCh 409.Of1.2005 for "drinking water" [17] or NCh 1333.Of1978mod1989 "water for irrigation" [18]. This condition limits their use to only a few crops such as corn, tomatoes, alfalfa, among others. Also, the soils of the Lluta Valley and the Camarones Valley, where these rivers are located, are affected by the poor quality of their waters, causing a lack of crop diversification [19]. This condition considerably affects the agricultural and livestock production sector and the local community. One of the most

important crops in this region is alfalfa production, which is the main feed for bovines and goats [16]. On the other hand, there is *Atriplex nummularia*, a halophyte shrub with protein characteristics similar to alfalfa, which could be an alternative for crop diversification [20].

Consequently, to mitigate this lack of water in quantity and quality, research on desalination technologies for water production is being carried out at the Universidad de Tarapacá (Arica and Parinacota region). To this end, a desalination plant has been implemented for the production of drinking water or irrigation. However, one of the problems generated by this type of plant was what to do with the brine produced. Considering this question, this work is expected to evaluate the use of brine for the production of halophytes (*A. nummularia*) considering the principles of circular economy in the region of Arica and Parinacota.

2. Desalinization

Desalination is a process of removing dissolved salts and other minerals from seawater or brackish water, resulting in freshwater and a subproduct called brine [21, 22]. Seawater desalination is an alternative that can extend water supplies beyond what is available in the hydrological cycle, with a constant and climate-independent supply [23]. The main desalination technologies include thermal methods such as multistage flash distillation (MSF) and multi-effect distillation (MED) and within membrane methods, reverse osmosis (RO). These desalination technologies commercially cover almost 90% of the world market. RO processes lead with a 53% share, followed by thermal technologies with 33% [24], and RO is a technology that has lower energy requirements, low complexity and, therefore, lower economic cost [25]. This technique requires electrical energy to activate a high-pressure pump, whereby the saline water is forced through semipermeable membranes to separate the freshwater (or product) from the saltwater (brine) [26]. However, despite the benefits offered by desalination, it is still an environmental challenge to consider the disposal of coproduced brine to mitigate the environmental impacts attributed to discharges into the environment. Generally, brine is discharged to the sewer or to the sea [27]. Currently, desalination technologies are also applied to treat the large amount of brine generated in these processes, which can be by electrodialysis [28] or by membrane distillation crystallization (MDC) [29], among other alternatives, in order to recover a greater volume of product water.

On the other part, being RO the most widely used technology, its performance depends largely on the type of membrane, which have a pore size <1 nm, allowing the passage of small molecules such as water and rejecting larger species such as Na^+, K^+, Cl^-, or dissolved organic compounds. In that sense, there are several studies that seek to improve and optimize the membrane material to generate higher permeability, better selectivity, and anti-incrustant properties [30].

2.1 Brine disposal methods

The most commonly used methods of brine disposal are i) discharge to the sea (surface and through multiport diffusers installed on the deep sea floor), ii) disposal in sewers (wastewater collection system, low cost and energy), iii) injections into deep wells (injected into porous subsurface rock formations), iv) injections into deep wells (injected into porous subsurface rock formations) (v) sewage disposal

(wastewater collection system, low cost and energy), (vi) deep well injections (injected into porous subsoil rock formations), (vii) land applications (irrigation of salt-tolerant crops and grasses), and (viii) evaporation ponds (evaporation of brine in ponds, salts accumulate at the base of the pond) [7]. In addition, when selecting the disposal technology, it is important to consider the location, quality, and volume of the brines [31].

2.1.1 Land applications

Among these applications, irrigation of crops with a concentrated solution of salts is a great solution in these times, considering that currently there is low-quality water available and that there is an increase in temperature worldwide, which is causing a greater demand for irrigation water [32], which is why having water, even if it is saline (brine), is a benefit to be considered.

Generally, the use of brine in sprinkler irrigation is common in parks, lawns, and golf courses, and also, in the cultivation of forage plants, which require low volumes of this solution. However, its use is limited for large volumes due to climatic conditions, plant size, seasonal demand, and depending on the stratigraphic and structural conditions where the subway aquifer is formed [33].

There are studies of halophyte plants such as *Arthrocnemum macrostachyum*, which indicate that this plant has a high capacity to desalinate soils. To this end, through an experimental analysis and under non-leaching conditions, soil salinity was reduced after 30 days of treatment by 31% (from 10.94 to 7.5 dS m^{-1}), regardless of whether the plant had been previously grown in the presence or absence of salt [34].

The means by which halophytes sequester salts and the degree of salt absorption differs according to plant species affect the efficiency of their use for remediation of affected soils. Halophytes have many productive applications: rehabilitating degraded lands, preventing desertification, providing firewood and timber, creating shade and shelter, and producing industrial crops and animal fodder. Halophytes can be grown on soils too saline for normal crops and pastures, from inland soils to soils near the sea, and thus can make a significant contribution to food security for living things [35].

Considering the above, it can be evaluated that this type of brine from desalination plants, when used in irrigation, presents advantages and disadvantages, which are described as follows:

Advantages

- Water availability (for irrigation).
- No environmental impact if brine is used for irrigation.
- Inland desalination plants compared to plants located in sectors avoid marine pollution.
- Soil degradation or seepage into groundwater is avoided if brine is added directly through injection from deep wells.
- Its use in aquaponics would allow to produce fish and at the same time to nourish the plants through an aquaculture recirculation system.

- There are plants that are tolerant to salinity (halophytes).
- Low capital cost by reusing the brine directly for irrigation of halophytes.
- Allows remediation of saline soils.

Disadvantages

- Not all plants are tolerant to high salinity concentrations.
- Risk of soil contamination if irrigated soils are microporous such as clay or silt soils.
- Not applicable for large volumes.

2.2 Brine disposal cost

One of the main problems in the installation of desalination plants is the cost of brine disposal, which is usually very high, ranging from 5 to 33% of the total cost of the desalination plant [7].

In addition, this cost depends on factors such as concentrate characteristics, treatment prior to disposal, disposal method, environmental regulations, location, concentrate volume, among others. It is also important to consider that the economic and environmental risks would be reduced if there is good management of brine use and final disposal. Así como también, es importante considerar que los riesgos económicos y ambientales se reducirían si existe una buena gestión del uso y disposición final de la salmuera [31].

2.3 Regulations applicable to brines

It is worth mentioning that among the few existing regulations worldwide, the Mexican regulation is a good option to start controlling the start-up of desalination plants and their waste. In this regulation called "PROY-NOM-013-CON AGUA/SEMARNAT-2015: that establishes specifications and requirements for intake and discharge works to be complied with in desalination plants or processes that generate brackish or saline rejection water," it indicates that it has 11 parameters and whose maximum limits include temperature, pH, total dissolved solids, turbidity, aluminum, copper, cadmium, among others. However, it does not refer to the main compound within the brine, NaCl [36].

Currently in Chile, there are no specific regulations related to desalination plants, as well as no regulatory system that considers the maximum concentration of brine expressed in NaCl, (mg L^{-1}) or salinity (dimensionless), or for the temperature (°C) for its final disposal, there is only a guide with minimum technical guidelines for desalination projects related to the jurisdiction of the maritime authority prepared by DIRECTEMAR [37] which includes desalination projects that may or may not be submitted to the Evaluación de Impacto Ambiental (SEIA) [38]. Cornejo-Ponce, et al. 2020 [7] proposed that both salinity and temperature, which are essential parameters, should have their upper limits expressed as follows: for salinity, the concentration should be less than or equal to that of the receiving mass. For example, if discharged into the sea, it should be lower than the salinity of the sea (35 mg L^{-1}), and for temperature, it should be considered approximately 2°C higher than that of the

Item	Equation	Definition
Charge balance	$Q_a = Q_p + Q_s$ (1)	
Rejection factor (R)	$R = (C_a - C_p)/C_a \times 100$ (2)	Corresponds to the rejection of salts from the membranes and in a membrane system, and it is the factor that determines the final quality of the product water of a distillation system.
Salt passage (SP)	$SP\ (\%) = 100 - R$ (3)	It corresponds to the ratio between the salt concentration of the product and the feed, measured as a percentage.
Conversion (Y)	$Y\ (\%) = Q_p/Q_a{*}100$ (4)	It corresponds to the percentage ratio between the permeate flow rate and the water flow rate entering the desalination process.
Concentration factor (CF)	$CF = 100/(100- Y)$ (5)	Corresponds to the number of times the brine is concentrated with respect to the feedwater.

Table 1.
Calculations involved in the desalination process [39, 40].

receiving mass, respecting the 2015 Paris agreement. In addition, once these parameters have been established, the different alternatives for their elimination can be evaluated.

2.4 Brine concentrate calculation

The calculations involved in the desalination process (**Table 1**) and specifically for obtaining the amount of brine produced consider a concentration of feedwater C_a (Kg m^{-3}), product water C_p (Kg m^{-3}), and brine C_s (Kg m^{-3}), as well as a flow rate of feedwater Q_a (m^3 h^{-1}), product Q_p (m^3 h^{-1}), and brine Q_s (m^3 h^{-1}) [39, 40].

3. Circular economy and brines

3.1 Why apply circular economy?

The world is changing; the economic, environmental, and social challenges facing today's society are becoming increasingly demanding. In this sense, the principle of the "circular economy" is a good way to make this approach more sustainable [39]. Whereas, over the past 10 years, private/public sector actors, governments, policymakers, citizens, the media, and the scientific community have been working to make the world more sustainable [41], changing the economic model from extract-use-dispose to an extract-use-reuse model. Thus, the circular economy seeks that system resources, energy, and materials are reused several times, considering a minimum processing for each subsequent use, through a closed loop. In other words, turning waste into a resource is an essential part of increasing our efficiency and moving toward a more circular economy [8].

In relation to the circular economy in water, in addition to complying with the reuse of this good, its quality and quantity must be prioritized [42]. Therefore, evaluating brine disposal management measures is an alternative to consider, depending on factors such as: (a) the volume or quantity of the concentrate, (b) quality of the concentrate, (c) physical and geographic location of the discharge point, (d) capital and operational costs, among others [43].

3.2 Circular economy principles

In addition, it is worth mentioning that the Office of Agricultural Studies and Policies, 2019 [44], proposed 3 principles and 11 strategies of circular economy, based on the World Economic Forum, 2018. Each principle is related to the strategies defined as follows:

Principle 1 Plan for the optimal use of resources

Design (R1): Integrate environmental impact in the development of products and services.

Reduce/Prevent (R2): Avoid use of unnecessary resources and prevent waste generation.

Optimize (R3): Maximize the usefulness of products, materials, resources, and assets.

Principle 2 Maximize the usefulness of materials at all times

Reuse/Distribute (R4): Take advantage of discarded or old products in good condition so that they fulfill their original function.

Repair (R5): Repair defective or old products to fulfill their original function.

Remanufacture (R6): Capture the value of components of discarded products to fulfill an original function, a new product.

Revaluate (R7): Transform discarded products, parts, or waste to condition a new function by capturing the value of materials.

Recycle (R8): Process materials to obtain products of equal or lower quality.

Recover (R9): Energy recovery by incineration of materials.

Principle 3 Preserve and improve the natural capital

Regenerate (R10): Regenerate natural ecosystems to promote positive impact on the environment.

Supply (R11): Procure sustainable supply of inputs with the least environmental impact.

3.3 Use of brine in halophyte plant cultivation under the principles of circular economy

The use of brines in saline agriculture can be beneficial, as it reduces the current demand for food production and maximizes water resources and the use of saline soils in accordance with the three principles of the circular economy (optimizing resources, maximizing the utility of materials, and preserving natural capital).

Today, it is possible to find salt-tolerant crops such as halophytes. These plants have developed a series of physiological and morphological adaptations that allow their tolerance to salt, and although they represent only 2% of terrestrial plant species, their domestication and cultivation in a context of saline agriculture may be interesting to consider [45].

Among the halophyte plants is the forage shrub *A. nummularia* (**Figure 1**), which grows in conditions of high salinity, requires little water, and has similar chemical properties to alfalfa. Despite being a shrub native to Australia, it is also grown in Chile, mainly in the north and can reach 3.5 m in height, is a common forage species in arid and semiarid regions, due to its tolerance to drought and salinity, can grow or can be planted in soil and/or saline water, and is also used as feed for bovine livestock [46].

In addition, there are studies in Brazil where they have cultivated forage plants irrigated with brine (obtained from RO), indicating that the yield for *A. nummularia* was 5.5–8.5 t. ha year^{-1}. The amount produced from the halophilic plant using brine is much higher than the value obtained in other arid parts of South America where it is grown as a wild crop [20, 47].



Figure 1.
Forage crop Atriplex nummularia *[46].*

4. Methodology

To achieve the objective of this work, it is proposed to follow the following flow chart of the research methodology to be carried out (**Figure 2**). For this purpose, the use of water from the Luta River, feedwater to be treated in the reverse osmosis desalination plant, from which product water and brine are obtained, is considered.

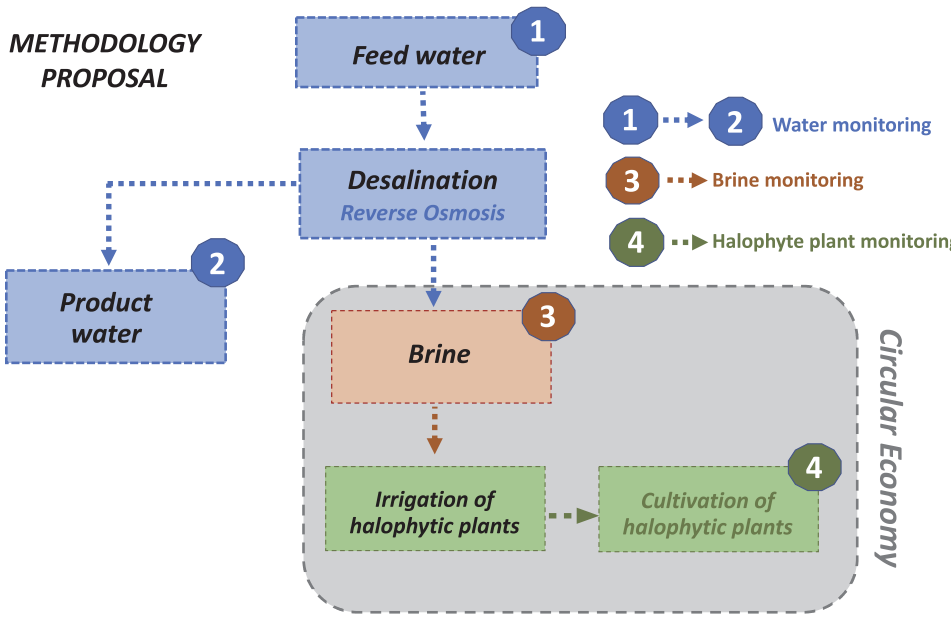


Figure 2.
Methodology for the use of brine for the production of halophyte plants (proper elaboration).

The latter is the subject of this publication. For this, according to the existing brine disposal factors, it is proposed as an alternative to minimize the potential environmental impacts to apply the 3 principles and 11 strategies of circular economy [44] for the cultivation of halophyte plants (*A. nummularia*).

In addition, the methodology is based on mathematical calculations to obtain information on flow rate and brine concentration, feed flow, among others, according to formulas in item 2.5 calculation of brine concentrate, considering the factors that influence brine disposal [43].

4.1 Reverse osmosis plant location

The reverse osmosis plant is located at the *"Plataforma Solar de Investigación y Entrenamiento: Tecnologías Solares para el Tratamiento de Agua"* at the Universidad de Tarapacá, city of Arica, in the region of Arica and Parinacota whose georeferencing is −18.4725111 latitude and − 70.3127704 longitude [48]. Among the activities developed in this platform is the applied research in solar water treatment, where several technologies have been implemented to obtain water, among which is the reverse osmosis; however, as mentioned earlier, the problem with this technology is: What to do with the brine generated?

4.2 Feedwater quality

The feedwater for the reverse osmosis plant was obtained from the Lluta River, which was transported by truck, in order to study real samples to generate information to support the rural communities that live in and use this water directly for their crops, limiting their diversification. The parameters used to determine the quality of the Lluta River feedwater were temperature, conductivity, pH, and total dissolved solids (TDSs). These were measured with a multiparameter apparatus (model HI 9828, HANNA Instruments, USA). The concentration of arsenic was also determined using the VARIAN FS 280 VGA 77 atomic absorption equipment with hydride generation and 950°C electrothermal blanket, which were analyzed according to international standards [49] at the Laboratorio de Investigación Ambiental de Zonas Áridas, LIMZA, of the Universidad de Tarapacá (Arica, Chile).

4.3 Soil quality in the lower Lluta River sector

To evaluate the quality of the soil in the sector adjacent to the Lluta River, samples were taken to determine parameters such as, texture, organic matter, pH, electrical conductivity, arsenic, available phosphorus, and total nitrogen, which were analyzed according to international standards [49] and the recommended methods of analysis for Chilean soils of the Comisión de Normalización y Acreditación (CNA), 2004 [50] at the Laboratorio de Investigación Ambiental de Zonas Áridas, LIMZA, of the Universidad de Tarapacá (Arica, Chile).

4.4 Reverse osmosis desalination plant characteristics

The pilot plant under study in this work corresponds to a reverse osmosis desalination plant, Wave Cyber Vessels, Model 300E 4" Side Port Housing, with 300 PSI (21 bar) maximum pressure, 49°C maximum temperature, −7°C minimum

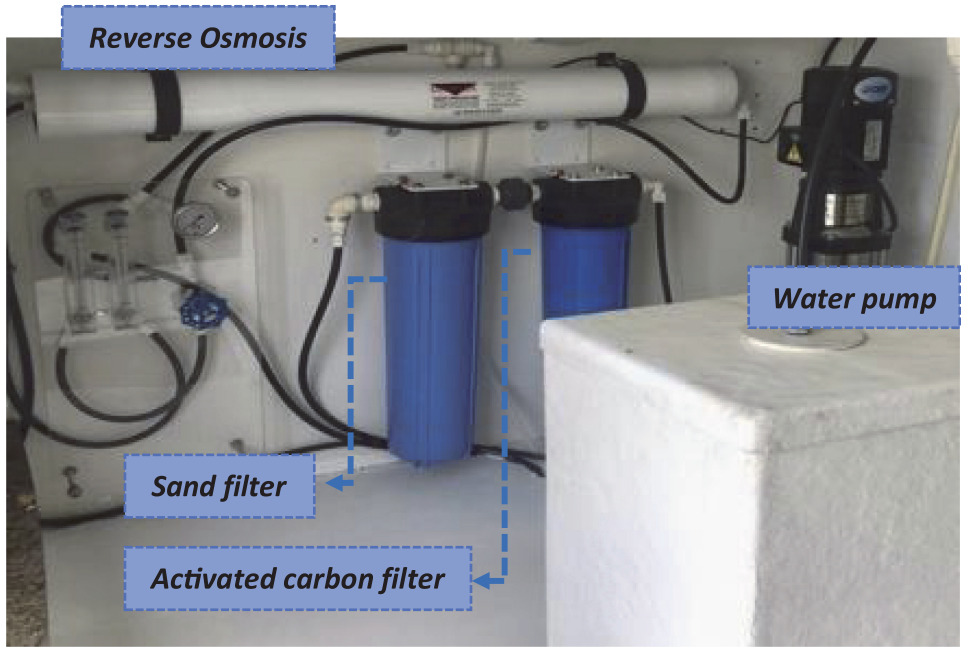


Figure 3.
Reverse osmosis plant (proper elaboration).

temperature, and dimensions of 328.2 cm in length. The product water yield is 360 L h^{-1} and the rejection factor is 50% brine [51].

The feedwater passes through a water pump first passing through sand and activated carbon filters, respectively. The 5-micron cartridge filter retains sediment (sand, sludge, and oxidation particles) to obtain clean water, and the granular carbon filter retains bacteria, chlorine, odors, and organic chemicals.

Subsequently, by reducing salts and compounds that can clog the membrane, it enters the osmosis system where arsenic and salts are reduced (**Figure 3**).

4.5 Application of the circular economy

The use of brine as irrigation water for the cultivation of halophytes (*Atriplex munmularia*) will be evaluated, considering the 3 principles and the 11 strategies of circular economy, taking into account point 3.2.

5. Results

5.1 Characterization of the water quality of the Lluta River

The Lluta River, located in the Lluta Valley, is a water system in which the physicochemical characteristics vary seasonally, mainly in summer due to the altiplanic summer rains. In addition, there are variations at different points along its course due to the presence of minor tributaries. The concentration of arsenic is notable, exceeding 29 times the value recommended by the WHO (10 mg L^{-1}) [52]. **Table 2** presents the physicochemical parameters of the Lluta River water.

Physicochemical parameters	Lluta River water values	NCh409/1.Of2005 drinking water	NCh1333. of 1978 Mod.1987 water for irrigation	Unit
pH	7.69	6.5 – 8.5	6.0 – 9.0	—
Electrical conductivity	1.52	—	—	$mScm^{-1}$
Temperature		—	30	°C
Chloride	528.1	400	200	mgL^{-1}
Sulfate	1,389	500	250	mgL^{-1}
Sodium	31.15	—	—	mgL^{-1}
Magnesium	41.14	125	—	mgL^{-1}
Calcium	174.05	—	—	mgL^{-1}
Arsenic	0.29	0.01	0.1	mgL^{-1}
Total dissolved solids	1,981	1,500	—	mgL^{-1}

Table 2.
Physicochemical characterization of the Lluta River water (proper elaboration).

5.2 Determination of soil quality in the Lluta Valley

In the Lluta Valley, mainly only corn (*Zea mays*) (*amylaceous*), alfalfa (*Medicago sativa*), onion (*Allium cepa L.*), garlic (*Allium sativum L.*), and beet (*Beta vulgaris var. Hortensis L.*) are grown. The soil use in the Lluta Valley is limited to these types of products due to high salinity, high concentrations of boron, chloride, and sodium, and drainage problems, as shown in **Table 3**, and physicochemical characteristics have historically affected the Lluta Valley, limiting the diversification of agricultural production systems.

5.3 Desalination process parameters

The calculation of the feed flow is made by means of Eq. (4), where Q_p is 360 L h^{-1} and the conversion is 50%, obtaining Q_a equal to 720 L h^{-1}. With the optimum flow rates of feedwater and plant product water, the brine flow rate is obtained by means of a load balance (Ec. (1)), with Q_s equal to 360 L h^{-1}.

To estimate the concentration of salts, present in the brine, a theoretical calculation was made, considering that the plant has a yield equal to Y (%) = 50. Through (Ec. (5)), the concentration factor (CF) is obtained, whose result is 2. This value was used to characterize the brine, multiplying its value by the initial concentration of each parameter of the Lluta River water (**Table 2**), where the results are expressed in **Table 4**.

Texture	Organic matter (% m/m)	pH	Electrical conductivity ($mScm^{-1}$)	Arsenic ($mgkg^{-1}$)	Available phosphorus ($mgkg^{-1}$)	Total nitrogen ($mgkg^{-1}$)
53.5% sand 14.5% clay 32% silt	1.80	6.88	2.34	276.6	26.5	0.61

Table 3.
Physicochemical characterization of the soil in the Lluta Valley (proper elaboration).

Physicochemical parameters	Values Brine	Unit
pH	7.9	—
Electrical conductivity	3.04	$mScm^{-1}$
Temperature	22.0	°C
Chloride	1,056.2	mgL^{-1}
Sulfate	2,778	mgL^{-1}
Sodium	62.30	mgL^{-1}
Magnesium	82.28	mgL^{-1}
Calcium	348.1	mgL^{-1}
Arsenic	0.58	mgL^{-1}
Total dissolved solids	2,962	mgL^{-1}

Table 4.
Theoretical characterization of the physicochemical parameters presents in the brine (proper elaboration).

5.4 Use of brine in halophyte cultivation

The present proposal considers the use of brine obtained from the RO plant, from which 360 L h^{-1} are generated (**Figure 4**). If we consider that the plant will operate 12 hours a day for 20 days a month, we obtain 86,400 L h^{-1} of this saline liquid waste, which can be stored in a pond to be used for irrigation.

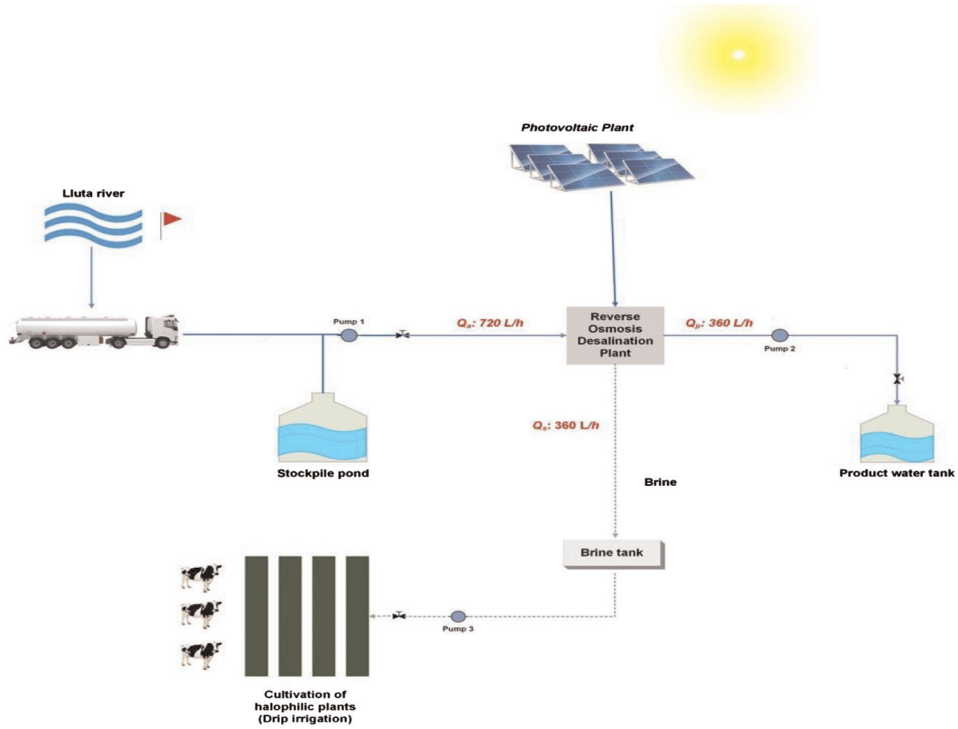


Figure 4.
Diagram of reverse osmosis plant and the use of brine in the cultivation of forage plants (proper elaboration).

The soil conditions for the cultivation of the fodder plant should be a fallowed, tracked, and leveled soil, where a drip irrigation system is established, whose Polyvinyl chlorid, PVC, lines could be at a depth of 40 cm. The plants can be produced in a nursery until they reach a size of 20 cm and then transplanted in furrows 1.5 m apart, conditions established for a cultivable land of 1000 m^2 [53]. In addition, the distance between plants should be 2.5 to 3 m because these forages generate a high volume of biomass [54]. It is proposed to cultivate 400 halophyte plants in a 1500 m^2 plot, considering an irrigation of 6 hours per week and a volume of 75 L $plant^{-1}$ $week^{-1}$ [19].

The production obtained from *A. nummularia* is 825 kg $year^{-1}$, according to information published by Sánchez et al., 2015 [20]. This fodder plant will be used to feed bovines or goats.

On the other hand, according to the comparison of the chemical analysis between alfalfa and *A. nummularia*, it can be observed that the latter has 4% more crude protein than alfalfa. Likewise, the dry matter and metabolizable energy of *Atriplex nummuralia* meet the optimal nutritional value for a dairy cow (**Table 5**).

It should be noted that the proposed system for the production of halophytes from brine will use 31.319 kWh day^{-1} (11,431.435 kWh $year^{-1}$) of electrical energy obtained from the photovoltaic system.

5.4.1 Effect of brines on soil physicochemical properties

Considering the chemical properties of the soil, the components detailed in **Table 3**, the Lluta Valley soil corresponds to the United States Department of Agriculture (USDA) textural triangle, being classified as a sandy loam soil [56].

In addition, it is worth mentioning that this type of soil has an apparent density of 1.50 g cm^{-3}, which indicates the space occupied by the pores in the soil in relation to the volume of water. In addition, these soils have a real density of 2.6 g cm^{-3}.

For the determination of the total porosity of the soil (ξ), it is calculated according to the following equation (Ec. (6)) [57]:

$$\xi = \left(1 - \frac{ad}{rd}\right) x\ 100 \tag{1}$$

Considering the equation x, we obtain a ξ =43% of total porosity.

This result indicates that they present spaces between the particles of 0.05–2 mm, increasing the size of the pore spaces between the particles and facilitating the drainage and aeration of the soil. This percentage also shows an adequate porosity for the development of halophyte plants. It is worth mentioning that halophyte plants are able to accumulate high concentrations of NaCl in their tissues, and there is

Nutrients	Alfalfa	*A. nummularia*	Optimum nutritional value for a dairy cow
Dry matter, %	89.7	88.1	20
Crude protein, %	16	20.2	18
Metabolizable energy, Mcal kg^{-1}	2.21	1.99	1.67–1.76

Table 5.
Chemical analysis of Atriplex nummularia *and alfalfa compared with optimal nutritional value for a bovine [20, 55].*

information of 39% in a shrub [58]. In addition, the use of halophytes plants for phytoremediation appears as a cost-effective, noninvasive alternative to other methods used for contaminated soils [34].

5.4.2 Effect of brine infiltration on soils

Each plant has a certain tolerance to salinity, depending on the plant species, the soil, and the characteristics of the brine. In general, some plants can tolerate TDS concentrations of 500 mgL^{-1}, and this is the case of halophytes that can be irrigated with a brine concentration higher than 2000 mgL^{-1} of TDS [58]. In general, soil texture is the main factor affecting the infiltration rate of soils, as well as soil depth, which makes the permeability characteristics of these different [59]. The soil under study has a sandy loam texture, whose infiltration rate is 0.8 to 1.2 cm h^{-1} (**Table 6**). This characteristic allows inferring that the soil for cultivation has a moderate infiltration rate, being optimal for drip irrigation [60].

On the other side, the capacity of the soil to retain water, called soil ponding capacity (PC), is another factor that influences infiltration, and in irrigation, it is always limited to a given depth (normally to the depth of roots). For the calculation of the ponding capacity (Ec. (7)), [61] was used, according to the data obtained in **Table 7** at a depth of 40 cm, obtaining a value of 48 mm. It is important to mention that the field capacity (FC) is the water content of a soil after having been abundantly irrigated and having drained freely for 24 to 48 hours, and the permanent wilting point (PWP) is the soil moisture condition in which the plants are unable to absorb water or do so with extreme difficulty, experiencing irreversible wilting:

Texture class	Basic infiltration rate (cm h^{-1})
Fine sand	1.2 a 1.9
Sandy loam soil	0.8 a 1.2
Silty loam soil	0.6 a 1
Clay	0.2 a 0.5

Table 6.
Basic infiltration rate according to soil texture class [60].

Texture	Ad Apparent density	FC Gravimetric soil water content at field capacity (%)	PWP Gravimetric soil water content at permanent wilting Point (%)
Sandy	1.5–1.8 (1.65)	6–12 (9.0)	2–6 (4)
Sandy loam	1.4–1.6 (1.50)	10–18 (14.0)	4–8 (6)
Loam	1.0–1.5 (1.25)	18–21 (19.5)	8–12 (10)
Clay loam	1.1–1.4 (1.25)	23–31 (27)	11–15 (13)
Sandy clay	1.2–1.4 (1.30)	27–35 (31)	13–17 (15)
Clayey	1.1–1.4 (1.30)	31–39 (35)	15–19 (17)

Table 7.
Physical properties for different textures [61].

Principles	Strategies	EC PRC
Plan for the optimal use of resources	R1 Design	The integrated design, which considers the use of photovoltaic panels to the reverse osmosis plant, allows to reduce the carbon footprint. In addition, the brine obtained from the RO process will be used to irrigate the *Atriplex nummularia* crop that will be used as feed for bovines and goats. It is worth mentioning that if the brine is disposed of in the local sewage system, environmental contamination is avoided.
	R2 Reduce/ Prevent	Avoiding the use of conventional electricity and using solar photovoltaic energy to generate electricity reduce greenhouse gases. Preventing brine from being disposed of in the sea or in sewage systems is a great relief for the environment and much better than using it to grow halophyte fodder crops for goats or bovines.
	R3 Optimize	Considering that if we have brackish water (720 L h^{-1}) and that when treated through RO, 50% product water (360 L h^{-1}) and 50% brine (360 L h^{-1}) are generated. The brine is generally disposed of in sewers, the sea or deep wells, but to maximize the resources, it is essential that the brine is used as irrigation water for halophyte plants, optimizing the use of feedwater by 100%.
Maximize the usefulness of materials at all times	R4 Reuse/ Distribute	Not applicable.
	R5 Repair	Parts such as water or brine storage ponds will be repaired, or any parts of the RO plant that have technical problems will be repaired. In addition, membrane regeneration periods will be provided due to membrane saturation, typical in brackish water use.
	R6 Remanufacture	The disused membranes will be used for applied research (new materials) and to generate new membranes in the laboratory LIMZA/UTA.
	R7 Revaluate	This project valorizes brine for irrigation of halophyte plants, reducing water consumption for irrigation and therefore reducing the cost of water consumption.
	R8 Recycle	Activated carbon bags are reused to store forage plants when they are available for animal consumption.
	R9 Recover	Not applicable.
Preserve and improve the natural capital	R10 Regenerate	The cultivation of halophyte plants helps to preserve the local natural resource and thus avoid environmental damage by disposing of the brine, for example, in the sea.
	R11 Supply	The electrical energy photovoltaic consumption of the system to produce halophyte is 11,431.435 kWh per year sustained with conventional energy would produce approximately 1.5 tons of CO_2 [62]

Table 8.
Principles and strategies of the circular economy applied to the cultivation of halophytes with brine obtained from the RO plant [44] (proper elaboration).

$$PC = \left(\frac{FC - PWP}{100}\right) x\ Ad\ x\ Sd \tag{2}$$

The PC value obtained indicates that the soil can store in a depth of 40 cm a height of water equivalent to 48 mm. However, not all of this water is available to the crop, since crops have different minimum water balances, for example, like halophyte, in the case of alfalfa, and in general, they require approximately 60% of the available water capacity to maintain evapotranspiration and avoid water stress.

5.5 Circular economy

This proposal was applied to the present work (**Table 8**), mentioning that strategies R1 to R3 are relevant for the optimal performance and utilization of the RO plant energetically sustained with solar energy, and that its resulting by-products are used for irrigation. From strategy R5 to R8, the products can be maximized through valorization, considering that the "brines" are allowed to produce "food" for other species such as "cattle or goats." In addition, membranes can be reused either by regenerating them or by using them to produce another type of membrane. As for strategies R10 and R11, they allow improving and preserving the natural ecosystem through the use of renewable energies, using the brine for irrigation, and reducing the use of conventional water.

Figure 5 is a proposal that considers three important components: 1. desalination plant, 2. photovoltaic system, and 3. halophyte cultivation. This integrated proposal

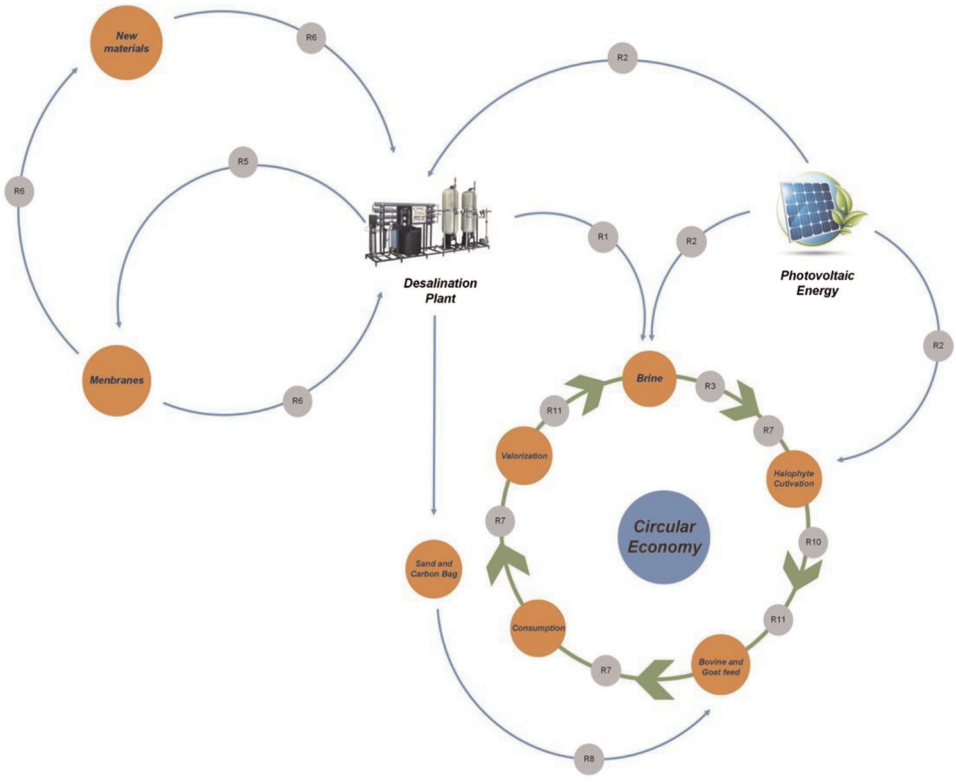


Figure 5.
Diagram of brine utilization in the cultivation of forage plants considering the principles of circular economy (proper elaboration).

would allow mainly rural communities to opt for the sustainable development of their products considering the circular economy in their processes.

Although, generally what is sought when implementing desalination plants is to obtain water for irrigation or human consumption; in this case, it is observed that the use of brine from this type of process serves for the cultivation of fodder plants. Therefore, environmental circularity would be achieved from the desalination plant by applying the different strategies of the circular economy.

Initially, the brine (R1) can be used for the cultivation of halophytes, reducing the consumption of irrigation water (R3 and R7). Subsequently, the fodder plant is used as feed for cattle and goats (R10 and R11), preserving the natural resource and reducing environmental pollution. It is worth mentioning that the valorization and consumption of animals fed with halophytes irrigated with brine should reduce production costs due to the water savings generated and the solar energy used as energy support for the system (R2).

Moreover, the desalination plant has parts that can be repaired (R5) or remanufactured (R6) or reevaluated (R7).

6. Conclusions and recommendations

The combination of the adaptation of technologies with natural brackish water and solar energy in the area would help mitigate the effects of climate change. In other words, the use of brine is a proposal that provides another source of water for irrigation and reduces the greenhouse effect. The proposed system to produce *A. nummularia* would avoid the production of 1.5 tons of CO_2 by using solar photovoltaic energy as the system's energy source.

The use of brine in the cultivation of the halophyte plant *A. nummularia* could generate a forage yield of 825 kg year^{-1}, occupying a volume of 75 L plant^{-1} week^{-1} of brine obtained from the RO plant. This forage obtained with *Atriplex* would contribute positively to the growth of bovines (cow), enhancing the sustainable development of the rural community.

In addition to the environmental benefits, the integrated scheme used in the semiarid region of Arica and Parinacota would produce a new source of food for the agricultural sector, thus, diversifying the fodder for livestock in rural areas and adding value to a waste stream with potential contaminating effects.

The use of brine as irrigation water for halophilic plants is an option to consider compared to conventional forage crops such as alfalfa. *A. nummularia* helps protect soils and subway aquifers, because it has a high salt absorption capacity, avoiding potential contaminating effects on the environment.

The circular economy can be considered as a valuable model to promote sustainable resource management, contributing to the construction of a vision for long-term sustainable development. Within this framework, the study complies with 9 of the 11 strategies of the circular economy.

The reverse osmosis technology produces a percentage of brine equal to that of the product water and researchers seek to improve and optimize the membranes to obtain more product water, in this particular case, it would not be necessary because the brine is used practically 100% in the irrigation of halophytes considering its cultivation in a sandy loam soil, with a pond capacity of 48 mm and a 43% of total porosity of the soil to be cultivated, introducing to this technology a new concept, circular economy, increasing its added value.

Finally, this study opens some potential opportunities for future research, such as the implementation of this type of projects in rural communities, considering the use of saline wastes as a source of water for irrigation, maintaining the circularity of RO desalination plants.

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Conflict of interest

"The authors declare no conflict of interest."

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