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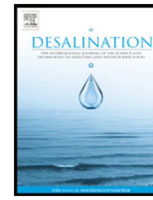

Uses of the reject brine from inland desalination for fish farming, *Spirulina* cultivation, and irrigation of forage shrub and crops

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HIGHLIGHTS

- Brine reject from inland desalination plants can have interesting agricultural uses.
- An integrated scheme that comprehends tilapia + *Atriplex* + goats is described.
- Results from 10 years of operation of this scheme are presented.
- Spirulina cultivation is an alternative to tilapia for the brine reject ponds.
- Irrigation and hydroponic cultivation of vegetables using brine were also tested.

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ABSTRACT

This paper offers a review on different experiences that have been conducted in South America, which are of interest for the agricultural use of the brine reject originated in inland desalination plants. The results obtained by a combined production scheme that uses brine reject from inland desalination plants for fish farming and for the irrigation of halophyte forage shrubs are summarized. This scheme has succeeded in turning an environmental problem (the brine reject disposal in inland areas) into a source of new economical activities. However, despite a slightly salt removal capacity shown by the halophytes, this production scheme was not able to prevent a progressive salinization of the land irrigated with the reject brine. The yields obtained are analyzed in terms of fish and forage production as well as the weight gain in the livestock fed with the halophytes. Also, due to its characteristics and good performance in arid regions and saline waters, the cultivation of *Spirulina* cyanobacteria is proposed as an alternative for fish farming within this production scheme. Finally, a series of South American studies addressing the irrigation of crops under saline conditions are reviewed, with the objective of establishing their potential use for reject brine management.

1. Introduction

The brine discharge in inland desalination plants remains a problem with few viable alternatives [1–4]. Diluting the brine in a water stream is not a feasible option as a small variation in the salinity levels of lakes and inland water courses can pose a serious environmental threat [5]. Also, brine can contain residues of pretreatment and cleaning chemicals, and their reaction byproducts [6].

Direct brine discharge in the soils would lead to its degradation by salinization. Pervious evaporation ponds [7,8] that allow percolation as well as the injection in shallow wells could pollute groundwater. In addition, salts may rise to the soil surface by capillary transport from a salt-laden water table and then accumulate due to evaporation. This issue is of particular importance in arid regions where there is already a man-made cause of salinization due to irrigation or due to an extensive use of potassium as fertilizer, which can form sylvite [9–11]. The process of salinization due to irrigation occurs when the salts dissolved in the water get accumulated in the soil. Since soil salinity makes it more difficult for plants to absorb soil moisture, these salts must be removed out of the plant root zone by applying an additional amount of water. This excess of irrigation is called the leaching fraction [12]. Together with an increase in the water consumption for irrigation, this subsurface drainage from agricultural fields can also produce large volumes of saline water [13,14].

The use of saline waters even at slightly above recommended values can have severe effects on soil resources [15]. If the land where the reject brine is disposed is of special environmental or agricultural value, a potential accumulation of salt minerals, ions or heavy metals should also be taken into consideration. In the deserts of the United Arabs

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Emirates, the reject brine from some desalination plants is disposed directly into surface impoundment in a permeable soil with low clay content, cation exchange capacity and organic matter content, and where the groundwater table lies at a depth of 100–150 m [16]. Even in these circumstances some impacts were detected in soil and groundwater, which pointed out the need of a management of the brine reject disposal [17].

The State-of-the-Art management of brine reject originated from inland desalination comprehends a range of techniques: evaporation ponds, WAIV (Wind Aided Intensified Evaporation) [18], discharge in shallow watercourses in combination with wastewater or other effluents, and deep well injection. The injection of the brine reject into deep aquifers poses many security issues and should only be applicable in confined aquifers. This technique has also been used in some desalination plants, using depleted oil wells. Deep injection has been carried out in the United States [19–22].

One approach of the management of brine involves the treatment of the reject brine to minimize the resulting flow and its salinity: two-step reverse osmosis with chemical precipitation between the stages (intermediate chemical demineralization) [23,24], two-step reverse osmosis with biological treatment between the stages [25,26], reverse osmosis with softening pre-treatment and high pH [27], two-step nanofiltration [28], and SPARRO process (Seeded Slurry Precipitation and Recycle Reverse Osmosis) [29–31]. Emerging technologies that are growing in importance are membrane distillation or pervaporation (*aka* pervaporative separation) [32], capacitive deionization [33], and FO (forward osmosis) [34–36]. The ZLD technique (Zero Liquid Discharge) may be of interest in those cases where the brine has heavy metals or other toxics that are wanted to be captured in the resulting solid product [37,38]. One solution for ZLD are evaporation–crystallization processes [39,40]. The evaporation–crystallization technology combines these two techniques to produce a solid residue (essentially calcium sulfate salts) from a liquid effluent. The energy consumption of this technique is high, and may be economically viable only in some particular cases, when associated with a vapor recovery system or waste heat. The use of solar energy could be of special interest for the increase in the viability of this technique.

Another approach focuses on the valorization of the brine reject stream. One research path aims the exploiting of the minerals contained in the brine by desalting procedures and the production of chemical products [41]. Separation of divalent salts from brines using extraction with organic solvent is technically feasible but to make the process economically viable is necessary to implement a solvent recovery system that allows its energy use [42]. A second research path regards the valorization of evaporation ponds. The main uses in order to add environmental and commercial value to evaporation ponds are aquaculture, irrigation of halophyte plants, which can be valuable sources of biofuel or fodder for cattle, and algaculture. Halophyte plants have also been used in revegetation to reclaim degraded land, providing a wildlife habitat and improving the soil. The production of microalgae using a brine reject stream mixed with wastewater as a source of phosphorus is of special interest in the treatment of brine rejects loaded with nitrogen compounds, which are generated in reclamation and reuse plants. Regarding algaculture, of particular interest is the cultivation of *Spirulina* cyanobacteria [43]. Halotolerant algae like *Gracilaria tenuistipitata* [44], the genus *Dunaliella* (*Dunaliella bardawil* and *Dunaliella salina*) and others [45] are a source of biological products (such as lipids and fatty acids) that may be isolated from the algal biomass. In addition, these algae are also relevant for biodiesel production [46].

Considering the valorization of evaporation ponds and the use of the brine reject generated from inland desalinization, a series of experiments have been carried out in South America in recent years, whose results can be of interest for the developing of similar projects in other parts of the world, especially in those with semi-arid climates.

South America has huge natural inland salt deposits located in arid zones. The Central Andes contain one of the most spectacular set of saline lakes and salt crusts in the world, with three major brine groups: alkaline, sulfate-rich, and calcium-rich brines [47].

Inland deposits of brackish waters are common also in the Gran Chaco region, a semi-arid lowland region divided among eastern Bolivia, Paraguay, northern Argentina and a portion of the Brazilian states of Mato Grosso and Mato Grosso do Sul [48]. A third vast region with brackish aquifers is the Northeast of Brazil which has a semi-arid climate and recurrent droughts.

Many arid zones of South America have aquifers that are naturally saline or have been salinized due to irrigation. These areas are generally populated by impoverished rural communities, whose income comes from livestock and irrigated agriculture. The lack of water constrains economic development, even when there are important mineral deposits, as in the case of the Atacama Desert (Chile). The use of the inland deposits of brackish groundwater can dramatically improve the life conditions of the local communities. Desalination through reverse osmosis is the most suitable solution in many cases, but together with its use comes the problem of brine disposal. Fig. 1 offers an outlook of the distribution of groundwater resources in Central and South America.

In Fig. 1, the light brown color refers to regions with minor groundwater resources in local and shallow aquifers. In these areas groundwater is limited to the alteration zone of the bedrock that locally may contain productive aquifers. Vast areas of the Pacific coast (Chile, Peru), the arid part of Argentina, Paraguay, and Bolivia as well as the Northeast part of Brazil stand out as the regions with the least groundwater resources.

The location of the Semi Arid region of Brazil is highlighted inside a red square. It is one of the largest semi-arid areas of the Americas, with 974,752 km^2 and a population of 22 million. In Fig. 2, the different soils that constitute the Northeast region of Brazil are classified according to their geological domain.

The areas colored in pink correspond to soils with fractured crystalline rock and low water potential. In these areas, aquifers are restricted to fracture zones represented by metasedimentary and metaigneous rocks from Archean to Proterozoic age, associated with a thin mantle (3–5 m) and located in the Semi Arid region. These are critical water stress areas due to low rainfall rates (yearly average of 500–700 mm) and high evapotranspiration values. The combination of these geological and climate conditions leads to problems of water salinization of soils and the presence of brackish groundwater. In these areas, brackish groundwater is available typically at a well depth of 40–80 m.

This part of Brazil is an exceptional example of inland desalination and brine management, partially because of a massive governmental program launched in 2004 named “Agua Doce” (Fresh Water) that has benefitted 150,000 inhabitants of the Semi Arid region [51]. Several small-size reverse osmosis plants were built to serve rural communities or to reinforce the supply of water in already existing networks that link several middle size municipalities. The selection criteria for the locations is based in lower rainfall rates, higher rates of child mortality, rates of poverty and human development, and lack of access to other sources of potable water supply. The region has a great availability of renewable sources [52], which make off-grid wind and solar systems suitable to power the small-size desalination RO plants developed in these rural areas. However, this option was finally disregarded by the Agua Doce Program and the RO units were connected to the existing electrical network, where available. Currently, local communities have access to the brackish groundwater through small wells that use tubular pumps coupled with reverse osmosis plants. Generally, the intake flow of these small-scale systems is up to 3 m^3/h, operating with an average recovery rate of 90% [50]. As a result, a waste stream of brine with high level of salinity is produced.

Values of brine from different RO inland plants in the region are shown in Table 1.

Electrical conductivity (EC) indirectly measures the amount of salts dissolved in the soil. Table 1 shows that brines with the same conductivity can have different contents of solutes. The predominant ones