Rejected brine recycling in hydroponic and thermo-solar evaporation systems for leisure and tourist facilities. Changing waste into raw material.

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Highlights

1. **Rejected brine from seawater desalination can be used as a mineral and water source for hydroponic culture**
2. **Rejected brine can be at the centre of a circular economy to reduce water consumption in leisure facilities**
3. **Tomatoes obtained with rejected brine culture are safe and have better organoleptic qualities**

Abstract

For more than 50 years the Canary Islands have been using seawater desalinization facilities in order to satisfy the freshwater demand of their main economic activity – tourism, which continues to contribute to the economic and social progress of the archipelago. However, this desalinization process involves the production of a “waste” product known as rejected brine, which is discharged from coastal regions and islands, whether it originates from public or private facilities. Rejected brines are potentially a serious threat to marine ecosystems. However, here we demonstrate that this “waste” can be processed and reused as a nutrient mineral solution for a hydroponic production system and also a source of freshwater. The efficiency of this management process in terms of fresh-water production and water recycling economy is also discussed. The aim of this paper is to change the attitude towards rejected brines, which should be treated as potential raw material to permit high savings in the running costs of leisure and tourist facilities around the archipelago. In addition, this will also have a positive effect on the environment, making desalinization more sustainable and environmentally friendly, which is nowadays an added value in customer and user satisfaction.

1. Introduction

1. Introduction

In the early decades of the past century, water scarcity was a predominant problem for the Canary Islands' economic and social development. This archipelago, located above the Tropic of Cancer (28-30º North latitude) in the Atlantic Ocean, has a hot arid climate in the south-facing half of its territory, while the other half has a warm damp climate due to the influence of the northeast Trade Winds and occasionally the North Atlantic Drift from the Gulf Stream. The scarce rainfall falls unevenly over the islands, with an average of 300 mm per year, making water a valuable resource in most of the territory [1]. As an example, in 1912 the Spanish Navy began to transport fresh water from the western to the eastern Canary Islands in order to ensure the population's needs. In this context, in 1964 the first Seawater Desalination Facility (SDF) in European territory was opened on Lanzarote. A year later, this first desalinated water production yielded 2300 m^3/day. Today, the archipelago has 319 Seawater Desalination Facilities (SDFs), with a daily fresh water production of over 650,000 m^3, according to data from the Canary Islands Government. However, only 30 of the SDFs are used by the public sector, while the rest are situated in leisure facilities, because tourism has become the driving force behind the economic and social transformation of the islands [2].

Since its initial implementation, seawater desalination in the Canaries has undergone important changes from the technological point of view. The initial distillation technologies used have been replaced today by reverse osmosis (RO) membranes in almost all SDFs [2], nowadays the archipelago has 332 RO plants with a daily water production of 588,057 m3/day [3]. However, despite these technological changes, seawater desalinization always involves a high economic and environmental cost, primarily through its dependence on fossil-fuel energy consumption [4]. A more efficient process requires lower carbon emissions and secondly the disposal of the rejected brine [5]. Seawater desalination achieves an average 42% water recovery ratio which means a rejected brine production of over 900,000 m^3 per day, which is discharged into the sea. Rejected brine is a serious threat to marine ecosystems, causing negative effects on both flora and fauna. This is especially so when the optimal initial high dilution capacity is lacking in the discharge system. Consequently, brine discharge plumes spread over large areas of the sea floor and modify the structure and distribution of benthic communities such as seagrass habitats [5]. The Canary archipelago has a large area of its coastline protected as a biosphere reserve (UNESCO), with unique ecosystems such as the *Cymodocea nodosa* (Ucria) seagrass meadows, which act as a nursery habitat for juvenile fish and other species [5]. Thus, in consequence, the sea disposal of rejected brine can lead to severe environmental threats, due to the vulnerability of these ecosystems to seawater salinity changes.

Rejected brine disposal costs are between 5 and 33% of the whole desalinization process, depending on the characteristics of the brine, its pretreatment level before disposal, disposal method, and volume [6] and [7]. Rejected brine management is today an important area of research; in this regard, zero-liquid discharge (ZLD) is considered an emerging technique to minimize waste. Although ZLD systems are capable of minimizing contamination of water sources (seawater in the present case) and increasing water supply, their industrial scale applications are restricted due to their high energy consumption and costs [8]. Therefore, these approaches are designed for large SDFs, while those used in leisure and tourist facilities around the Canaries will probably require new design and implementation strategies. This may have a huge impact on the overall running costs of suchfacilities, and also a positive effect through becoming more sustainable and environmentally friendly, which is an accepted requirement nowadays for customer and user satisfaction [9].

A simple use of rejected brine has been soil irrigation, especially for halophytic crops. However, these species have a low yield potential mainly due to the metabolic energy cost of salt tolerance mechanisms, which drastically diminish their yield as crops, especially when compared with non-halophyte species [10]. Additionally, rejected brine will have a deleterious effect on soil because of its excessive ion content, especially sodium, over the time leading to high yield losses and soil degradation [11]. However, not all salinity effects on non-halophyte crops are deleterious, since specific aspects such as visual quality, soluble solids content, and titrable acidity are also enhanced under salinity stress [12]. These aspects of product quality open up the possibility to reuse rejected brine as a nutrient solution or as an amendment in hydroponic systems, after a readjustment in its chemical composition. In fact, nowadays hydroponic systems have been already implemented in tourist facilities to produce fresh vegetables for their clients' daily consumption [13].

The aim of this article is to report how rejected brine from SDFs within leisure and tourist facilities can be used as a source of specific nutrients for hydroponic tomato production (*Lycopersicon esculentum* L.), and also of fresh water through a thermo-solar evaporation system. This fresh water obtained can be reintroduced into the complex water system, thus reducing the volume needed from the desalinization process. This strategy could change the hotel-owners' attitude to rejected brine disposal along the Canary Islands coastline, and encourage them to start treating it as a potential raw material. It would therefore improve the sustainability of tourist facilities. Finally, we will discuss the efficiency of this process in terms of fresh water production and water recycling economy based around the leisure and tourist facilities.

2. Material and Methods

2.1 Rejected brine analysis and hydroponic nutrient solution design

Rejected brines (RB) used in all the experiments were collected from a Reverse Osmosis desalination facility with isobaric chambers. This produces 28,800 m3/day, which is supplied to the city of Santa Cruz, Tenerife, by the company EMMASA SL. As chemical treatments the company only uses an antiscalant provided by Nalco. Chemical analyses of all RB were performed using an ICP-OES AVIO500 (Perkin Elmer), before being transformed into a nutrient solution.

The transformation began by comparing the RB chemical composition with Hoagland´s standard nutrient solution [14]. From this comparison, a series of dilutions were performed in the RB (1/25 and 1/40) in order to reduce specific toxic ion levels (Na^+, Cl^- and B). The selected dilutions were transformed by specific amendments following the calculations using the Nutrient Solution Calculator datasheet provided by Dr. Incrocci (Dipartimento di Biologia delle Piante Agrarie, University of Pisa) to attain

Hoagland´s nutrient content. These modified nutrient solutions were prepared from RB for each of the experiments.

2.2 RB nutrient solution tests in laboratory hydroponic systems

The assays using RB nutrient solutions for tomato growth and fruit production were performed using *Lycopersicon esculentum L*. var. Microtom plants in a 40 L capacity recirculating hydroponic system in each experimental replicate. Plants were raised in a growth chamber at 22°C, 16 h light (PPFD 700 µmol m^{-2} s^{-1}) and 60-70% relative humidity. Each individual hydroponic system constituted an experimental group with 20 plants for each treatment. Microtom seeds were sown in a glasshouse with commercial potting substrate for 3 weeks. Then the substrate was washed gently, trying not to break the roots and transplanted directly to the hydroponic system, with a 10 cm distance between plants. During the first seven days, the hydroponic nutrient solution was half-concentrated Hoagland´s solution. Later, plants were selected and distributed between three experimental groups, according to the nutrient solution used. The electrical conductivities (EC) of the RB nutrient solutions were 7 dS/cm for RB 1/25 and 5 dS/cm for RB 1/40. Hoagland´s solution was used as control. All the solutions were replaced every two weeks, keeping the pH at 5.5.

2.3 RB nutrient solution tests in a commercial scale glasshouse

Commercial glasshouse experiments used rainwater for the dilutions of RB. Four 10 m long recirculating hydroponic systems were built, using 16 cm diameter plastic tubes with a 300 L capacity deposit for the solution. Conductivity and pH were measured every week. The pH was adjusted between 5.5-6.0 and the EC for the control group was set below 2 dS/cm and for RB 1/40 nutrient solution between 5-6 dS/cm. To adjust the pH, HCL or NaOH were used and nutrient stocks were added when the solution conductivities were lower than those tested weekly during the experiment. Water was added when the solution conductivity was higher.

Commercial *Lycopersicon esculentum* L. var. Capa negra plants were used in all the experiments. Seeds were sown in a glasshouse with commercial potting substrate for 3 weeks, then the substrate was gently washed off, trying not to break the roots, and transplanted directly to the hydroponic system, with 1m distance between plants. Two replicates of 10 plants were used for each nutrient solution. Plants were grown in half-concentrated Hoagland´s nutrient solution for a week before changing to a Hoagland´s (Control) or RB 1/40 solution. Tomato plants were subjected to the same largely routine horticultural procedures in the glasshouse until the end of the experiments.

2.4 Fruit yield and commercial quality analysis

Hydroponic tomato yield in both control and RB 1/40 nutrient solution was quantified by collecting and weighing all tomato fruits. Yield is expressed as the average weight in grams per fruit, and their number and kg per plant. Additionally, measurements of commercial quality parameters were conducted on 20 fruits from the different experimental treatments.

The non-destructive analyses used were: colour using a colorimeter (CR-400 Chroma Meter, Konica Minolta) set to CIELAB analysis mode; dry matter by drying the tomato for five days at 65 ºC and weighing), total soluble solids (TSS) using a digital refractometer (HI96801, Hanna Instruments); hardness tested at 4 points around the "equator" of tomatoes by a non-destructive hardness tester (53215TP, Turoni, Italy), then tested again at another 4 points around the equator after removing skin.

Firmness was quantified using a destructive penetrometer (PCE-PTR 200). Titrable acidity (TA) defined as % citric acid was determined by titration with 0.1 M NaOH using an automatic device (HI84432, Hanna Instruments), and pH by using a food-compatible pH-meter (MW100+MA920B1, Milwaukee, U.S.A.). Finally, leaves and fruit mineral content were measured in an ICP-OES AVIO500 (Perkin Elmer), using 4 individual samples from each treatment.

2.5 Rejected brine solar evaporator system

To determine the amount of distilled water obtained from the RB, a static solar evaporator (Supplementary Fig. 1) was constructed with two sheets of glass joined in an aluminium frame over a black tray, where 1 L of brine was deposited and sealed to avoid evaporation loss. The volume of evaporated water was measured daily for a week and the temperature, relative humidity and insolation conditions were recorded by a meteorological station less than 1km away from the evaporator. These data allowed us to determine the volume of distilled water produced by the evaporator per m^2 per day. Water mineral content was analysed in an ICP-OES AVIO500 (Perkin Elmer).

2.5 Statistical procedure

Statistical analyses for yield experiments were performed by one-way ANOVA and the significance of differences between experimental groups was calculated using a Tamhane post-hoc test. Additionally, the other parameters were analysed using a T-Student test. All statistical tests were performed with IBM-SPSS20 software.

3. Results

3.1 Brine analysis confirms useful mineral concentration of K^+, Ca^{+2}, Mg^{+2}

Mineral analysis of the RB showed extremely high concentrations of Na^+, Cl^- and B, which make direct use of the brine as nutrient solution unviable. However, it also presented moderately high concentrations of plant macronutrients such as K^+, Ca^{2+}, Mg^{2+}, with values from 2 to 32-fold higher than Hoagland's nutrient solution. The rest of the ions showed concentrations below, slightly over or at the same level as the Hoagland (Table 1).

To use the RB as nutrient solution, a series of dilutions and amendments were made in order to minimize the deleterious effects of Na^+, Cl^- and B on plant growth and development and to keep the rest of the ion concentrations similar to Hoagland solution. Table 1 shows the dilutions used from the RB (1/25 and 1/40) and the values in the table were the amendments used to reach the ion concentration levels of the Hoagland. These dilutions presented an EC of 7 (1/25) and 4 (1/40) dS cm^{-1} and a pH between 5.5-6, which was monitored during the experiments. However, despite the dilutions and amendments used for the RB dilutions, the final Na^+, Cl^- and B concentrations were still well above those of the Hoagland solution with 32.2, 7.9 mmol L^{-1} (Na^+ and Cl^-) and 194 µmol L^{-1}(B) for the 1/25 dilution and 23.2, 4.9 mmol L^{-1} (Na^+ and Cl^-) and 121 µmol L^{-1} (B) for 1/40.

Table 1. Rejected brine ion analysis

				RB Dilution Amendments		**RB Nutrient Solutions**	
	Ions	**H-Sol.**	**RB**	**1/25**	**1/40**	**1/25**	**1/40**
mmol L^{-1}	N-NO$_3$	14	1.9	13.9	13.9	14	14
	N-NH$_4$	1.0	0.0	1.0	1.0	1.0	1.0
	P-PO$_4$	1.0	3.0	0.8	0.9	1.0	1.0
	K$^+$	6.0	**11**	5.5	5.7	6.0	6.0
	Ca^{2+}	4.0	**8.5**	3.6	3.8	4.0	4.0
	Mg^{2+}	2.0	**64**	0	0.38	2.0	2.0
	Na$^+$	0.0	**928**	0.0	0.0	**32.2**	**23.2**
	S-SO$_4$	2.0	**23.1**	1.07	1.42	2.0	2.0
	Cl$^-$	0.0	**199**	0.0	0.0	**7.9**	**4.9**
µmmol L^{-1}	Fe	45	15	44.6	44.6	45	45
	B	48	**4861**	0.0	0.0	**194**	**121**
	Cu	1.0	0.0	1.0	1.0	1.0	1.0
	Zn	1.0	0.1	1.0	1.0	1.0	1.0
	Mn	10	0.3	9.9	9.9	10	10
	Mo	1.0	0.0	1.0	1.0	1.0	1.0
Cost (m^3 Euros)		**2.36**				**1.86**	**1.94**

The first two columns show the ion analysis in ppm of Hoagland Nutrient Solution (H-Sol) and the reject brine (RB) from EMMASA S.L. The next two columns present the amendments to the RB dilutions (1/25 and 1/40) in order to reduce the nutrient content of the Hoagland solution. The last two columns are the final ion concentrations in the RB (1/25 and 1/40) nutrient solutions used in the lab and greenhouse experiments. The cost in Euros for the Hoagland nutrient solution and the RB 1/25 and 1/40 nutrient solutions was calculated for 1 m^3.

3.2 RB nutritional formulation experiments under laboratory hydroponic systems

Once the RB nutrient solutions were formulated, they were tested under laboratory conditions in a recirculating hydroponic system. The main goal of the experiments was to verify that RB formulations allowed Microtom plants to grow, flower and fructify, independently of their deleterious effects. Under experimental conditions, Microtom plant growth was slightly reduced by both RB formulations when compared with control plants. However, no symptoms of nutritional deficiencies or toxicity were found during their vegetative growth, flowering period or fruit development (data not shown).

RB formulations did not show a negative effect on fruit weight produced by Microtom plants; on the contrary, both RB nutritive solutions showed similar or slightly higher fruit fresh weight when compared with control plants (Fig. 1A). However, yield (expressed as g fruit/plant) behaved differently, showing drastic reductions (57%) in RB 1/25 nutrient solution and a moderate reduction (27%) in RB 1/40 solution, compared to control plants (Fig. 1B). These differences were linked to the number of tomatoes per plant produced under experimental conditions. In fact, control plants produced 10 more fruits per plant than those grown in 1/25 RB nutrient solution but only 6 more than in 1/40 RB nutrient solution plants. Overall, the number of fruits/plant in the control group was 37% higher than the average number in either RB nutrient solution (Fig. 1C). Nevertheless, total soluble solids, a variable associated with the amount of soluble sugars present in the fruits, was significantly higher in both RB nutrient solutions than in control plants (Fig. 1D). Taking all these results together, it was decided to use 1/40 RB nutrient solution to scale up the experiments to greenhouse production conditions.

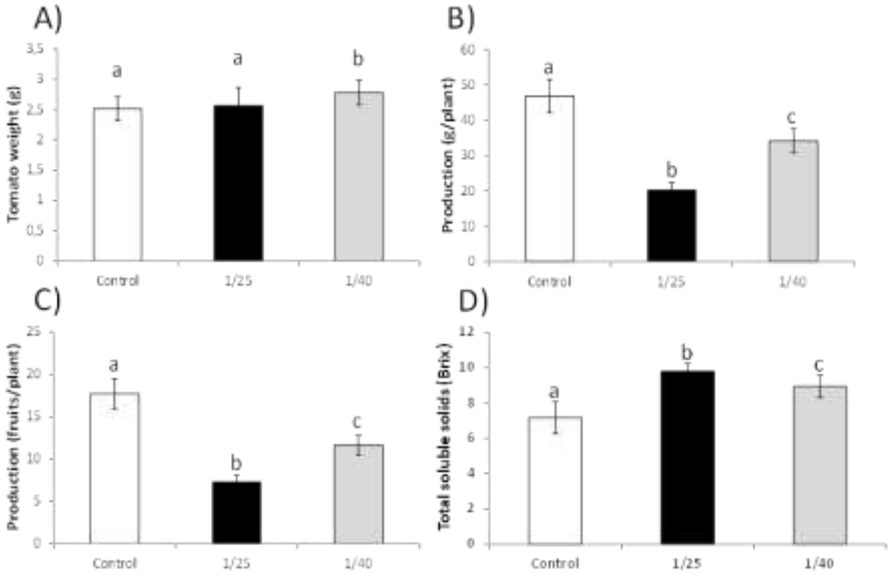

Figure 1: Measurements used to select reject brine dilution on solution optimization. A) Microtom tomato weight average, B) Production measures g/plant, C) Number of fruits per plant, D) Total soluble solids expressed as Brix°. Values followed by different letters are significantly different at $p<0.05$.

3.3 RB nutrient solution in a commercial greenhouse using a hydroponic system

As mentioned before, greenhouse experiments were undertaken using a commercial tomato variety (Capa Negra) in a hydroponic system with RB 1/40 nutrient solution. Under experimental conditions, no significant differences were found in plant growth. Neither were there symptoms of nutritional deficiencies or toxicity detected during vegetative growth, flowering period or fruit development (Supplementary Fig. 2). However, mineral leaf ions analysis during vegetative growth did show significant differences between RB 1/40 nutrient solution and control plants. These were in macronutrients such as P and Ca and almost all the micronutrients (Table2).

A similar trend to that observed in Microtom plants under laboratory experiments was detected in the greenhouse, after analysing the productivity variable, quantified as kg/plant and number of fruits/plant (Fig. 2). In addition, tomatoes grown in RB 1/40 nutrient solution showed a significant reduction in fresh weight (40%), together with a 37% and 34% reductions in kg/plant and num. fruits/plant respectively, compared to control plants. Analysing other variables such as skin hardness and pulp firmness (Fig. 3), tomatoes grown in RB nutrient solution had a slightly softer skin (statistically significant) than those of control plants (Fig. 3A). These differences were even higher when pulp firmness was analysed, showing a significant 12% reduction in RB 1/40 produced tomatoes (Fig. 3B). The other variables analysed to assess their organoleptic quality showed completely different behaviour (Figure 4). Tomatoes formed under RB 1/40 nutrient solution presented significantly higher levels of total soluble solids (17%) and dry matter (33%), compared to control. Differences in titrable acidity expressed as the percentage of citric were even higher (34%) between the two groups, as well as significantly lower pH values. Tomato colour analysis showed significant statistical differences between Control and RB 1/40 fruits in all CIELAB analysed parameters (Fig. 5A). In fact, when these parameters were transformed to RGB colour values in order to accurately represent fruit skin colour, wide differences appear between groups (Fig. 5B). Tomatoes irrigated with RB 1/40 showed a brighter skin tone with high intensity in the red and yellow colours, together with a higher saturation or intensity and a lower contribution from secondary colours such as green, blue and purple.

Figure 2

Figure 2: Productivity measures of tomato growth in a commercial glasshouse with or without reject brine. A) Tomato weight average, B) Production measures kg/plant, and C) number of fruits per plant. Values followed by different letters are significantly different at p<0.05.

Figure 3

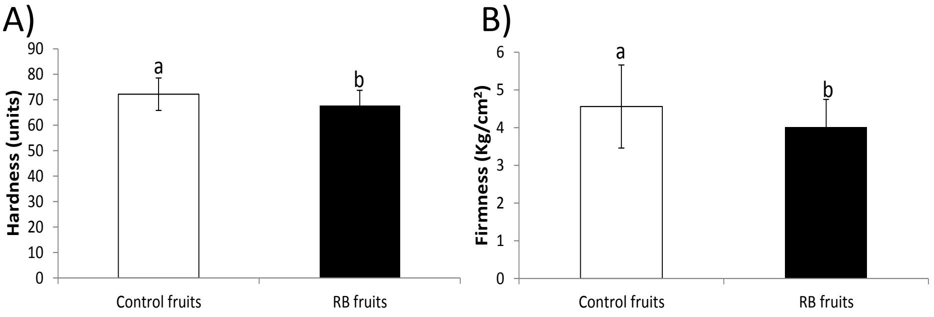

Figure 3: Hardness and firmness measures of tomato growth in a commercial greenhouse with or without reject brine. A) Skin hardness, B) Pulp firmness. Values followed by different letters are significantly different at p<0.05.

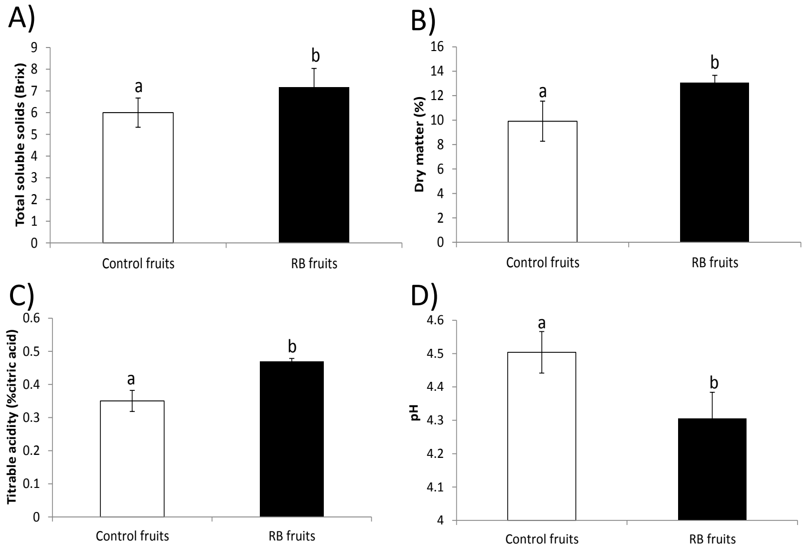

Figure 4

Figure 4: Organoleptic measures of tomato growth in a commercial greenhouse with or without reject brine. A) Total soluble solids represented as Brixº, B) percent of tomato dry matter, C) titrable acidity represented as % of citric acid, D) tomato juice pH. Values followed by different letters are significantly different at p<0.05.

Figure 5

A)

	L*	a*	b*	C	H
Control	42.1±1.7	37.5±2.7	38.4±3.5	53.7±2.1	45.7±0.7
RB 1/40	44.3±1.6*	46.7±2.6*	41.4±3.1*	62.5±3.2*	41.5±1.2*

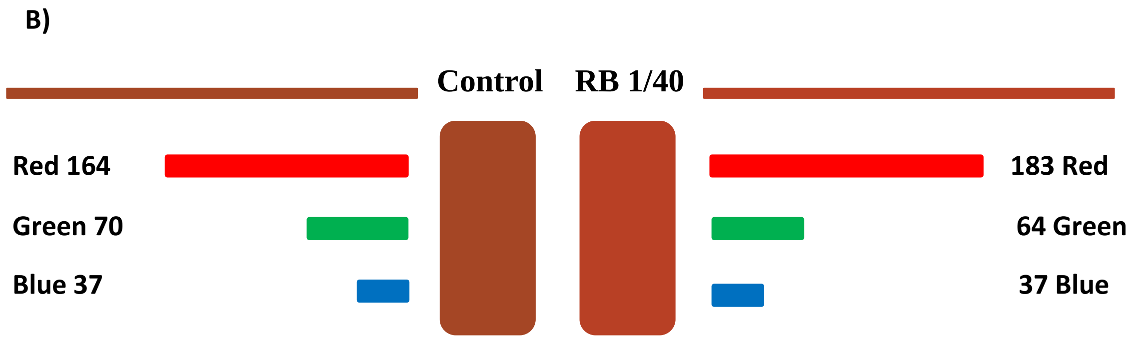

Figure 5. Fruit colour analysis of tomatoes from control and RB1/40 hydroponic nutrient solutions. **(A)** CIELAB colour measurements analysis decomposed as L* values for brightness; a* for redness or greenness; b* for yellowness-blueness. The Chroma parameter C defined as C = [(a*)2 + (b*)2]0.5 measures colour saturation or intensity and the hue angle (H = arc tan b*/a*) quantifies the red, yellow, green, blue, purple or intermediate colours between adjacent pairs of these basic colours. **(B)** CIELAB variables were transformed to RGB to represent colour differences in tomato skins. All colour parameters were transformed using a website converter (Colormine.org). * means that values are significant differently from the control at p-value< 0.05

Finally, tomato fruit mineral analysis showed substantial differences between the RB 1/40 nutrient solution and control plants (Table 2). Fruits produced in RB nutrient solution showed important concentration differences in macronutrients such as Ca and Mg, with a significant decrease of 38% and 46%, respectively. However, RB tomatoes exhibited 90%, 83% and 28% increases in Na, P and K, respectively. Micronutrients also presented differences, especially Zn, Fe and Cu, with 100%, 91% and 24% decreases, respectively.

Table 2 Changes in mineral concentration in control and reject brine leaves and tomatoes.

	%						ppm				
	N	P	K^+	Ca	Mg	Na	Fe	Mn	Cu	Zn	B
Control Leaves	2.8±0.05	0.55±0.01	3.55±0.04	4.08±0.05	1.07±007	0.5±0.007	248±11.8	167±4.4	14±1.3	74±4.6	148±5.6
RB Leaves	**2.5±0.1**	**0.26±0.01**	**3.13±0.21**	**2.82±0.09**	**0.9±0.03**	**2.7±0.09**	**148±7.7**	**71±1.7**	**10±0.7**	**43±1. 4**	**77±2.2**
Control Tomatoes	1.9±0.1	0.06±0.002	1.3±0.04	0.013±0.0004	0.013±0.0004	0.0195±0.0005	14.2±0.4	0	14.5±0.4	10.5±0.3	30.5±1.9
RB Tomatoes	2 ±0.1	**0.11±0.003**	**1.67±0.05**	**0.008±0.0002**	**0.007±0.0002**	**0.2±0.0006**	**1.2±0.04**	0	**11±0.3**	0	28±1.8

Data show the mean values plus their standard deviation. Comparisons between leaves and tomatoes (in bold) are significantly different at $p<0.05$

3.4 Ion analysis of surplus hydroponic solution

Mineral content in the hydroponic nutrient solution was analysed during and at the end of the greenhouse production experiments; the results are shown in Table 3. The analysis showed a significant increase in macronutrient concentrations, such as Ca, K and Mg. This increase was even more drastic in micronutrient concentrations such as Fe, B and Cu, well above the standard levels of the reference Hoagland nutrient solution. In addition, Na concentration was nearly 14 times lower than the concentration found in RB. These changes in ion concentration levels were associated with the volume of the surplus solution left at the end of the experiments, a 50% reduction compared to the beginning of the experiments.

Table 3. Surplus solution ion concentration.

	Ions	Surplus solution concentration	Hoagland solution concentration
Mmol L^{-1}	Ca^{2+}	9.01	4
	K^{+}	16.21	6
	Mg^{2+}	3.58	2
	Na^{+}	66.92	0
µmol L^{-1}	Fe^{2+}	57.5	45
	B	46.3	48.6
	Cu^{2+}	3	1

Data show the concentration in surplus solution after one week, compared to Hoagland solution with regard to plant nutritional needs.

3.5 Efficiency of the thermosolar evaporation system

A modest-sized pilot thermosolar evaporation system was built in order to assess the amount of water directly recoverable from an RB solution (Supplementary Fig. 1). Using our design, an average of 1.1 L day^{-1} was obtained in a period of 8 days, and the volume of water evaporated was highly correlated with the solar radiation received by the evaporation system (r^2=0.89; Fig. 6). The mineral analysis showed that the composition of the evaporated water was similar to distilled water (Data not shown).

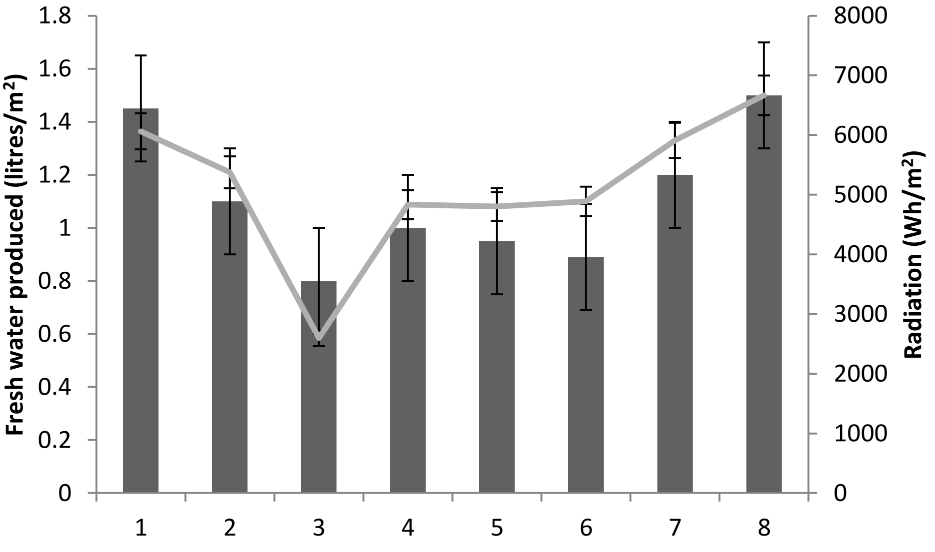

Figure 6: Water production by thermosolar evaporation of reject brine. Fresh water produced by rejected brine evaporation is represented in the graph by bars the and average radiation is represented by the line. Figure shows the average of two repetitions of an 8-day period.

4. Discussion

In recent years, it has become widely accepted that we must be ready to respond to increasing drought events at any scale [15]. In Spain, desalination has been presented since about 2000 as the cure for all problems in water scarcity, principally for coastal regions on the Mediterranean Sea [16] or Atlantic Ocean [2]. As can be seen, desalinated water is a powerful option to combat drought but it raises various concerns regarding land, groundwater and marine contamination, besides the added energy consumption [17]. Desalination plants located near the shoreline often discharge untreated brine directly into the sea [18]. Faced with increasing water demand coupled with water scarcity intensification, desalination is expected to expand rapidly in the future. The expected expansion in desalination capacity will be accompanied by an increase in the volume of brine produced. Management of the rejected brine is a still a major problem of desalination [19], owing to both elevated salinity and chemicals used during pre- and post-treatment phases in the desalination operation [19]. The high salinity of brine also causes elevated density in comparison to the receiving waters, which can form “brine underflows” across the sea bottom that deplete dissolved oxygen and affect marine life. High salinity and reduced dissolved oxygen levels can have a profound impact on benthic organisms, which can have ecological effects observable throughout the food chain [20]. These drawbacks require the development of new brine management strategies that are both economically feasible and environmentally sound [21].

Comprehensive reviews of the recent techniques, technologies and innovation in brine management are provided in [7], [8] and [22]. Other potential economic opportunities offered by brine production have also sparked a wave of innovation in brine management that seeks to turn an environmental problem into an economic advantage, such as its uses in aquaculture, Spirulina cultivation, and irrigation of halophytic forage shrubs and crops [23]. Meanwhile, here in the Canary Islands approximately 20 Hm^3 of brine are generated by leisure and tourist facilities per year, which has a negative environmental impact on the coastal flora and fauna [5] and [24]. The techniques designed and described for larger-scale desalination plants [6-8] and [22] can be really hard to implement in a hotel environment [7]. The average tourist complex in the Canaries has more than 300 rooms and requires the installation of a small desalination plant to ensure a fresh water supply.

Here, we propose the use of RB as a mineral and water source, to introduce a circular economy based on this waste-product, implementing a hydroponic greenhouse inside leisure complexes as a sustainability attraction for their guests (Fig. 7). The idea consists of channelling RB directly from the desalination plant to an evaporation chamber. This water is used for dilution of RB as a mineral source, mixed with amendments to prepare the hydroponic nutrient solution. It must be pointed out that use of a 1/40 solution provides a 20% saving in the cost of nutrient minerals (Table 1). As an example, using data from the hotels described in [25], an average fresh water consumption of 453.5 m^3 per week generates 626.1 m^3 of RB in the same time. The installation of a greenhouse to cultivate 200 tomato plants involves the use of 4 m^3 per week of hydroponic solution in our experimental conditions. Using our pilot set-up, this amount of water is provided by a thermosolar evaporator that feeds the cultivation system, recycling less than 1% of the total RB generated by the hotel desalination facilities.

Figure 7.

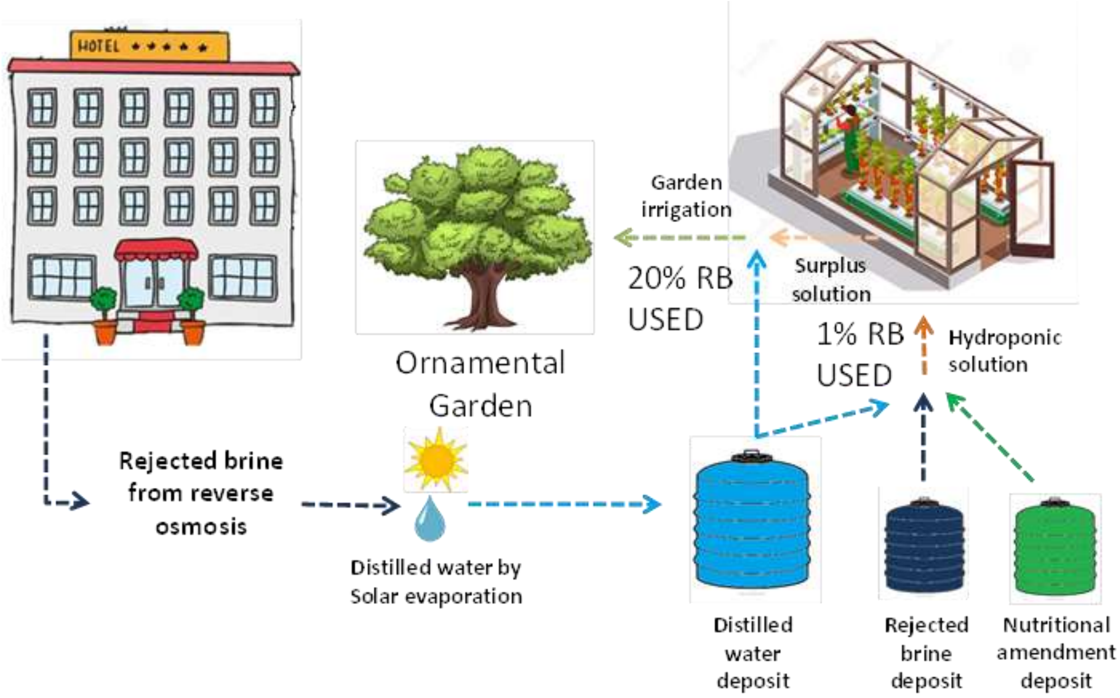

Figure 7: Hypothetical set-up of the proposed system

One problem in these conditions is the amount of water produced by the evaporation chamber. With our efficiency level (Fig. 6), an evaporative surface-area of 280 m^2 is necessary to feed the cultivation system with fresh water. However, our evaporation chamber with good insolation is in theory capable of producing 4 L per day [26], which reduces the space requirements by half, moreover nowadays there are other improved thermosolar evaporation systems [26-27]. Another option to obtain water from RB is to use membrane distillation technology [28], which offers some advantages in managing RB in comparison with other evaporation systems: 1) low operating temperatures; 2) theoretically 100% ion rejection; 3) alternative energy sources such as solar can be used to drive it; 4) compact process size [28]. A solar-energy membrane distillation system [29] had a maximum distillate water recovery of 3.4 L/h m^2. This system with an operating time of 14 hours per day yields 333 L/m^2 per week [29]. In fact, using only 12 m^2, enough fresh water would be supplied for our hydroponic cultivation. However, these data are based on seawater, not RB; for this reason further research is necessary. Another way to increase the efficiency is the technology used to facilitate Membrane and Thermal Processes Integration described in [30]. These systems achieve 81% fresh water recovery. This technology could be added to our trial recycling set up with the proper adjustments, helping tourism facilities to manage these wastes more economically and sustainably.

After the tomato cultivation trial according to our pilot scheme (Fig. 7), one hypothetical alternative to increase the amount of RB recycled would be to use the surplus solution left in the hydroponic system. In our experimental conditions, hydroponic solution deposits lost half of their water each week (obtaining 2 m^3 each week). Analyses of our surplus solution showed that it provides a valuable concentration of macro- and micro-nutrients (Table 3), and after a 1/10 dilution it had an electrical conductivity of 1.22 mS/m and low Na^+ concentration (less than 6.6 mM). It is therefore potentially suitable for agricultural irrigation [31], but needs special monitoring regarding soil salinity parameters [32]. Using the same example as in the above paragraph [25], leisure complexes in the Canaries use an average 12% of their total water consumption in garden irrigation, which means 54.5 m^3 per week. This can be supplied by RB evaporation; using 150 m^2 of the described system [29] and a 500 m^2 greenhouse to accommodate 500 tomato plants, enough surplus solution and water are provided to supply the irrigation solution. Altogether, the systems (Fig. 7) recycle or reuse RB directly as a resource that brings a direct saving of 12% in water consumption for irrigation and a direct use of 20% of the RB, also enhancing the environmentally friendly brand of the leisure facilities. Moreover, the improvement in brine evaporation techniques can be applied to direct re-utilization of “grey water” produced by the leisure facilities, reducing their water requirements and making for a real circular management of RB by tourist facilities.

An important question is the quality of the fruits cultivated with RB. In our conditions, yield dropped by about 40% (Fig. 2), which is common when growing tomatoes using high-conductivity solutions. A study using a similar conductivity solution (5-6 dS/m) underwent a drop in yield near 30% [33]. At the beginning of the study, one of our concerns was the safety of RB used as a mineral source, arising from the possible absorption of heavy metals into fruit, or microbiological contamination. However, none of our analyses detected unpermitted levels of metals or boron in RB or fruits, and in microbiological analyses no *Escherichia coli*, *Enterococcus* or *Clostridium perfringens* were found (data not shown). Another important concern was about nutrient disorders in fruits, especially tomato blossom-end rot, which is one of its most common disorders, commonly associated with calcium deficiency [34]. Reject brine contributes approximately 10% of the calcium used in the hydroponic solution. As seen in Table 2, calcium was significantly lower in RB-grown leaves and fruits, but without any symptoms of such nutritional disorders (Supplementary Fig. 2). These differences may be within the normal range in plants grown in salinity conditions, because Na^+ can disturb or disrupt the normal absorption of other cations, especially Ca^{2+} [35]. Other parameters commonly linked to calcium are hardness and firmness [36]; only the second is significantly different in RB tomatoes (Fig. 3). This is a common effect in tomato cultivation under salinity [37]. Furthermore, RB had a significant positive effect on fruit quality parameters (Fig. 4), with an increase in total soluble solids, dry matter, percentage of citric acid and low pH. The tomatoes additionally presented a bright red colour compared to control (Fig. 5), thus being more tempting for hotel consumers. Moreover, red colour in tomatoes is correlated to lycopene concentration [38] and antioxidant content [39] that are interesting as preventive anticancer agents [40], giving an extra boost to the reputation of RB tomatoes. This is a common feature in this crop under high electrical conductivity in the root zone, leading to increased concentrations of dry matter, sugars, and titrable acid in the fruit [36] and [41]. Finally, it is important to point out that salinity can enhance quality in a plethora of vegetables, see review [12], making cultivation with rejected brine a good option for better organoleptic vegetables to supply leisure facility kitchens.

Taken together, these results suggest that the use of RB as primary source of minerals for hydroponics induces a growth penalty, but the implementation of this system next to the desalination plant of hotels would provide their kitchens with their own tomatoes and other vegetables, with better organoleptic qualities according to our trials.

5. Conclusions

Seawater desalination using reverse osmosis technologies is now important as the main source of fresh water in the Canary archipelago. Large tourism facilities located on islands have their own desalination equipment in order to satisfy their clients’ water requirements. The rejected brine from these installations is usually dumped or discharged into the environment, usually the sea, which endangers coastal ecosystems. We propose the use of this brine as a mineral source for hydroponic culture, which leisure facilities can use as environmentally friendly or “green” publicity through supplying better fruits and vegetables with exceptional organoleptic qualities for their customers.

The use of RB at a dilution of 1/40 directly saves 20% of hydroponic solution cost due to the nutritive minerals present in the brine. Growing tomatoes under saline conditions provided by RB gives them excellent organoleptic qualities, as shown by their total soluble solids, dry matter percentage, titrable acidity and pH. The high quality parameters of RB-fed tomatoes encourage the implementation of this technology next to the desalination plants of hotels, to provide their kitchens with better-tasting vegetables ‘at source.

Water for nutrient solutions can be provided by an RB thermosolar evaporator-condenser (solar still), such as the customized ‘homemade’ system developed in our conditions. An evaporative surface-area of 280 m2 is necessary to feed 200 tomato plants. However, better location and design of solar stills can decrease the surface area requirements.

Finally, we discuss how to further enhance the environmental management of the hotel RB by using the surplus solution generated in the greenhouse for garden irrigation and fertilization. For this, the system requires the use of an improved evaporation-condensation design, to produce fresh or low-salinity irrigtion water for extensive hotel gardens. This system is particularly focused on managing brine from small desalination facilities like those commonly installed in hotels, with an improved evaporation technology such as membrane distillation with solar energy. Rejected brine can thus be an important source of minerals and water for hydroponic cultivation, and finally for garden irrigation. The implementation of this process would enhance the ecological value and reputation of tourist facilities, for instance by providing an eco-friendly brand image for a hotel, the most important achievement being the revalorization of an otherwise harmful waste-product.

6. Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

7. Author Contribution Statement

David Jiménez-Arias: Conceptualization, Investigation and Data curator; Sarai Morales-Sierra: Investigation; Francisco J. García-Machado: Investigation; Ana L. García-García: Investigation; Juan C. Luis: Writing - Original Draft; F. Valdés: Writing - Review & Editing; Luisa M. Sandalio: Writing - Review & Editing; Manuel Hernández-Suárez: Resources provider; Andrés A. Borges: Funding acquisition and supervision

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