1 Title: Exploring the Agricultural Reutilisation of Desalination Reject Brine from Reverse
2 Osmosis Technology

3 Authors & affiliations:

4 David Jiménez-Arias^{a*}, Sarai Morales Sierra^b, Francisco J. García-Machado^a, Ana L. García-
5 García^a, Andrés A. Borges^a, Juan C. Luis^b.

6 ^a Chemical Plant Defence Activators Group, Department of Agrobiology, IPNA-CSIC, Avda.
7 Astrofísico Francisco Sánchez 3, P.O. Box 195, 38206 La Laguna, Tenerife, Canary Islands,
8 Spain

9 ^b Grupo de Biología Vegetal Aplicada (GBVA), Departamento de Botánica, Ecología y
10 Fisiología Vegetal – Facultad de Farmacia, Universidad de La Laguna, Avda. Astrofísico
11 Francisco Sánchez s/n, 38071 La Laguna, Tenerife, Canary Islands, Spain

12 *Corresponding author: David.j.a1983@gmail.com

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14 Floriculture

15 **Highlights**

16 1. Reject brine is a constant and reliable source of minerals that can be used as a raw material in
17 hydroponic culture.

18 2. Brines analysed in various countries have a rich content of plant nutrients, showing the
19 feasibility of using brine salts within the agricultural context.

20 3. A circular economy based on sustainable brine management offers reduced crop production
21 costs using a hydroponic facility, along with possible further secondary incomes.

22 **Abstract**

23 Among its other effects, climate change is driving humanity into water scarcity, especially in
24 highly populated areas such as the Mediterranean. One of the best options to solve this problem
25 is seawater desalination, but it has its environmental, social and economic impacts. The brine
26 reject effluent from the process can be used as a rich mineral source for hydroponic culture.
27 Indeed, stability in its composition was shown here during a one-year study. A compilation of

analyses from desalination facilities located worldwide also demonstrates how reutilisation of this liquid waste can provide an opportunity to build a circular economy based on brine management. Potential profitable crops and an economic study of its implementation are discussed. Correct brine management channelled into an agricultural context can be an excellent way to improve the public and ecological reputation of desalination. It can also yield extra income beyond the fresh water yield from the proposed system.

1. Introduction

Intense industrialisation and high urbanisation rates combined with climate change are the main contributors to the water crisis affecting many parts of the planet [1], while agriculture consumes approximately 60% of available water resources in developed countries [2]. Worldwide, from 1983 to 2009, 454 million cultivated hectares suffered yield reductions due to drought problems, causing losses that could reach 143€ billion [3]. Lack of fresh water is acutely worrying in Europe and even more dramatic in the Mediterranean area, where its availability is expected to again reach levels below those of 1990 [4]. The rest of the world will likely follow a similar trend, with estimations of severe water scarcity in more than 60 countries [5]. In the 21st century, this disturbing scenario has caused the emergence and development of new technologies to obtain fresh water. The most encouraging method is desalination [6].

Desalination capacity has been increasing by 7% on average per year [7], reaching 97.2 million m³/day [8]. The most widely used feed source is seawater, 58.9%, followed by brackish groundwater (21.2%) [6]. More than 20 different technologies are used nowadays for seawater desalination, however Reverse Osmosis is the most widely used in small and medium facilities, covering 69% of the installed water desalination capacity [9], so it will be focused on here. Brine from seawater desalination is one of the most promising sources of fresh water for securing the global water supply [10]. It offers significant advantages when compared with other sources, owing to its sustainable supply. However, a debate about the environmental costs of desalination is emerging in society nowadays [11–13], focused on more careful brine management and reducing the high energy costs of running the facilities, which are factors limiting its expansion [8,11–14]. Social acceptance is one of the most common problems when a new facility is to be established near urban areas [15]. However, the too-frequent “not in my backyard” way of

thinking is not sustainable [16]. It is therefore necessary to look for new strategies to overcome or assuage the prevalent opinion and gain public acceptance.

Brine production was estimated at 141.5 million m³/day in 2019 [8], and several studies have described how coastal brine discharge affects benthic ecosystems [17–20]. Alternatives to reduce brine impacts explore dilution, mixing, diffusion jets and their drastic reduction using minimum- and zero-liquid discharge approaches [21]. However, applying this technology in practice requires more feasibility studies [22]. In addition, the quantity of surplus brine itself has inspired researchers to work towards different ways of transforming this otherwise contaminant waste product into a useful resource. Many studies have tried to use brine as a source of valuable elements [23], and the authors calculated appreciable revenues from what they call "seawater mining" to offset the cost of the desalination process. Sodium hydroxide can be produced using seawater brine as a source [24], or greenhouses can be cooled by evaporating it, obtaining salt in the process [25]. Brine can be used for halophytic crops by soil irrigation [26], but it has deleterious effects over time. These lead to soil degradation and consequent yield losses in later non-halophytic plants [27], which prevent this type of application in most cases. Finally, other studies point out the potential of using brines in fish farming, spirulina cultivation, and irrigating forage shrubs [28], and also to produce β -carotene [29]. These projects open exciting new avenues for direct brine utilisation.

Previous work [30] demonstrated that, with simple modifications, reject brine can be used as a nutritive solution for crop production in a hydroponic system. As a bonus, fruits produced in this way had better organoleptic parameters after growth under saline conditions. Consequently, soilless agriculture and horticulture should be considered as alternative reuse channels for part of this brine, as it has significant advantages over traditional cultivation methods. For instance: i) sites can be located near desalination facilities, avoiding the problem of low availability of agricultural land [31,32], ii) this also avoids soil degradation by brine due to its excessive ionic content [27], iii) brine minerals can be used to reduce the quantity of nutrients needed to produce a balanced complete hydroponic solution [30]. As mentioned before, reject seawater brine contains considerable amounts of minerals essential for plant growth, such as Ca^{2+} , Mg^{2+} , and K^{+} , commonly known as macronutrients [30]. Use of brine in hydroponic systems installed near desalination facilities can yield other profitable benefits and savings. Several by-products with

agricultural and horticultural uses can be manufactured from it, as an attractive way to generate new income and also enhance public acceptance of this technology [33,34].

This study focuses on reutilising the desalination brine from Reverse Osmosis facilities. With this end, a one-year assessment is presented here of five desalination facilities on Tenerife (the largest of the Canary Islands). It shows how reject brine can be a constant and excellent source of minerals to feed hydroponic facilities. Furthermore, the potential international implementation of this approach is supported by analyses of brine effluent from reverse osmosis desalination facilities in mainland Spain, published data from several countries, and the nutritional requirements of different crops.

2. Material and methods

2.1 Reject seawater brine samples

Sample acquisition from Tenerife began in November 2019 and concluded in November 2020. The local brine samples came from 5 reverse-osmosis desalination facilities around the island. The second set of samples from two facilities in the Mediterranean was received in August 2020.

Table 1. Desalination facilities used in the study

Desalination facility	Production	Location
A	4000 m ³ /day	Urban zone
B	500 m ³ /day	Urban zone
C	4000 m ³ /day	Agricultural zone
D	1800 m ³ /day	Agricultural zone
E	5000 m ³ /day	Agricultural zone
Alicante	65000 m ³ /day	Urban zone
Murcia	57000 m ³ /day	Urban zone

2.2 Reject brine analyses

A total of 180 samples from Tenerife were analysed in triplicate. One replicate from each desalination facility was taken from the Mediterranean samples. Macronutrients (Ca²⁺, K⁺ and Mg²⁺), sodium, micronutrients (Cu, Mn, Fe and B) and heavy metals (As, Hg, Cd and Ni) were quantified using an ICP-OES AVIO500 (Perkin Elmer). For anions (Cl⁻, NO₃⁻, PO₄⁻³, SO₄⁻²) the ionic chromatographer 883 Basic IC plus (Metrohm AG) was used, fitted with a Metrosep A,

Supp. 5 250/4 mm column (Metrohm AG). The mobile phases were water/H₂SO₄ 100 mM and Na₂CO₃/NaHCO₃ 3.2 mM and 1 mM, respectively.

2.3 Reject brine transformation

The transformation began by comparing the brine chemical composition with Hoagland's standard nutrient solution[35]. A series of dilutions were necessary to reduce specific toxic ion levels (Na⁺, Cl⁻ and B). The selected dilution was transformed by specific amendments (listed in tables 5,6 and supplementary 1 to 7), following the Nutrient Solution Calculator datasheet provided by Incrocci (Dipartimento di Biologia delle Piante Agrarie, University of Pisa) to attain Hoagland's nutrient content [35]. This transformed solution was assessed for its environmental and economic costs and used in various agricultural and horticultural crops.

2.4 Statistical procedures.

One-way ANOVA and a Tamhane *post hoc* test were applied to analyse the significance of differences between experimental groups, using IBM-SPSS20 software.

3. Results and Discussion.

3.1 Mineral analysis of local reject seawater brine. Location vs. time comparison.

Reject brine analysis showed high macronutrient ion content, especially Ca²⁺, K⁺, Mg²⁺. Sodium reached levels above 16 g L⁻¹ in the brine; it is not considered a macronutrient but has a significant effect on nutritive solution conductivity, to be discussed in the following sections. For plants, inorganic salts dissolved in water are the primary source of mineral ions such as Ca²⁺, K⁺ and Mg²⁺ [36]. These minerals play essential roles in plant growth, flowering and fruit development, critical factors in crop production. Previous work in the present research line showed how using reject brine was both an excellent source of macronutrients and a way to reduce the cost of nutrient mineral solutions by 20%, and also how to minimise productivity losses due to high Na⁺ levels in a commercial crop [30]. Each brine sample and results came from a single desalination facility at a specific location at a particular time of year.

In order to establish if a constant supply of Ca²⁺, K⁺, and Mg²⁺ can be achieved all year round, brine from five desalination facilities at different locations on the island of Tenerife was analysed monthly. The results showed Ca²⁺ concentration variations during the experimental period, from

350 to 750 ppm; however, values were similar in the five desalination plants studied (Figure1A). It is interesting how its concentration fell in all studied facilities in November, reaching minimum values in December, except for one where this minimum was in January. From these minima, Ca^{2+} concentration rose to maximum levels in March-May, slowly falling again during the following months until November, at all desalination facilities. However, one-year average Ca^{2+} concentration showed statistically non-significant differences between the different locations (Figure 1B), always above 500 ppm (12.1 mmol L^{-1}). These values were 22 times higher than the concentration needed for a standard hydroponic solution like Hoagland's [35]. Reject brine seems a reliable source of Ca^{2+} , and showed no calcium-associated disorders in tomato plants in previous work [30]. Calcium is considered one of the essential elements in plant growth and development, also acting as a messenger in responses to biotic and abiotic stresses [37]. It is moreover extremely important in post-harvest fruit quality [38]. Calcium disorders or deficiencies cause many plant disorders, resulting in critical economic losses [39–41]. Clearly, a correct and constant Ca^{2+} supply will enhance crop growth quality and defence, especially under hydroponic systems [42,43].

Figure 1. Seawater calcium analyses of brine from five desalination facilities on Tenerife. A) Monthly reject brine analysis during the one-year period. B) One-year concentration average for each facility, listed with letters A to E.

Potassium showed higher concentrations compared to Ca^{2+} (Figure 2B). A minimum of 700 ppm and maximum 1050 ppm concentrations were registered, according to desalination facility and year. Despite these differences, average K^{+} concentrations were always between 800 to 900 ppm at all facilities (Figure 2B). The exceptions were registered between February and May, when all

the analyses showed an increase in K^+ concentrations, but only in three desalination facilities in July (Figure 2A). It is noteworthy that the three facilities with the highest K^+ levels in July are next to vast banana plantations. In the May-July period, banana plants reach the fruit set period, which requires higher nutritional elements, especially potassium, finishing at the end of July [44]. This excess fertilisation could affect nearshore waters [45], resulting in a K^+ increase in the reject brine deriving from intake seawater. On average, K^+ concentrations in brine were 850 ppm (22 mmol L^{-1}), ten times more than a regular Hoagland solution [35]. It is therefore a reliable and demonstrated source of K^+ in crop production [30]. Potassium is essential in plant production, and appropriate K^+ fertilization demonstrated reductions in yield losses [46]. Previous research showed how K^+ deficiency limited water-use efficiency in economically important crops such as wheat, maize or sugar beet [47], being critical in stomatal closure/aperture processes [48]. It also modulates responses against environmental stresses such as salinity, drought and metal toxicity [49], affecting plant growth and metabolism, due to its involvement in carbohydrate and protein biosynthesis, and enzyme activation [50].

Figure 2. Potassium analyses of seawater brine from five desalination facilities on Tenerife. A) Monthly reject brine analysis results during the one-year period. B) One-year concentration average for each desalination facility, listed with letters A to E.

Magnesium had the highest concentrations of all macronutrients analysed in the reject brines (Figure 2A). It showed relatively constant levels during the twelve months monitored, with a significant increase in April and May (Figure 3A). Annual average levels were statistically non-significant between the facilities (Figure 3B), reaching values above 2000 ppm ($82.26 \text{ mmol L}^{-1}$). These Mg^{2+} concentrations enable a 40 times dilution of the reject brine, as demonstrated in previous work [30], enabling plant vegetative growth and fruit production without any

deficiency. Magnesium plays a central role in the structure of the chlorophyll molecule, acting as the pillar of photosynthetic activity [51]. It is involved in many enzyme activities, for example, reactive oxygen species homoeostasis and structural tissue stabilisation [52]. However, beyond the essential role of Mg^{2+} in plants, it is noteworthy that hypomagnesaemia is known to contribute to several chronic human diseases [53]. Moreover, nearly two-thirds of the world population does not consume the recommended amount of Mg [54]. This is probably because Mg^{2+} concentrations in food crops have decreased over time [55], for two main reasons: i) most agricultural soils are acidic (about 70%) and Mg^{2+} solubility decreases at low pH [56]; ii) drought periods caused by climate change lower the amount of Mg^{2+} available for plants [57]. Consequently, seawater brines are a perfect source of enormous amounts of this mineral, easily incorporated and accumulated by plants [30], to obtain crops with the recommended nutrient concentrations for human health. Crop biofortification could become a future research field to explore with brine contents.

Figure 3. Magnesium analyses of seawater brine from five desalination facilities on Tenerife. A) Monthly reject brine analysis during the one-year period. B) Annual concentration average for each desalination facility, listed with letters A to E.

The analysis also showed higher amounts of the anion Cl^- , reaching concentrations above 30 g/l and a total absence of carbonates. Table 2 summarises anion concentrations, notably high levels of SO_4 and low levels of other essential macronutrients, PO_4 and NO_3 . These SO_4 levels together with the Cl^- must be taken into account when preparing the final solution, preferentially using nutrient PO_4 and NO_3 for the final amendments.

Table 2. One-year average anion concentrations

Desalination facility

Anion/ppm	A	B	C	D	E
Cl ⁻	29285 ± 5118	29534 ± 5973	29147 ± 9123	30151 ± 6276	29437 ± 5959
NO ₃ ⁻	7.8 ± 4.1	6.8 ± 7.1	17.1 ± 6.1	12.7 ± 5.1	10.8 ± 8.1
PO ₄ ⁻³	66.1 ± 24.9	54.3 ± 13.5	74.7 ± 21.4	83.7 ± 28.4	89 ± 35.9
SO ₄ ⁻²	2045.2 ± 485	2200 ± 543	2391.1 ± 591.5	2726.3 ± 628.5	2111.4 ± 745.9

Finally, micronutrients and heavy metals were analysed. Micronutrients in nutritional terms are negligible, except for boron, which reached averages above 12 ppm or 1.1 mmol (Table 3). These values are approximately 40 times higher than those needed to mix a balanced nutritive solution [35]. Heavy metals (Table 3) are presented in ppb. Before dilution, except for Hg from some desalination facilities, they showed quantities lower than the maximum permitted in vegetables by the World Health Organisation [58]. However, the working dilutions are usually higher than 1/40, and previous work demonstrates how heavy metals were not accumulated in tomato fruits [30]. In addition, no *Escherichia coli*, *Enterococcus* or *Clostridium perfringens* were found (data not shown) in the reject brine analysis. This is consistent with previous findings because *E coli*, for instance, is not able to survive after 72h in a 20% NaCl solution [59].

Table 3. Year-long average macronutrient and heavy metal concentrations

	Desalination facility					Permitted levels in foodII
	A	B	C	D	E	
Micronutrients ppm						
Cu	1.3 ± 0.3	1.3 ± 0.3	1.2 ± 0.1	1.2 ± 0.1	2.4 ± 1	
Mn	4.8 ± 2.3	2.6 ± 0.1	3 ± 0.7	2.4 ± 0.1	2.7 ± 0.3	
Fe	6.8 ± 2.3	2.5 ± 2	2 ± 1.6	1.5 ± 2	1.2 ± 2	
B	19.7 ± 3	16.1 ± 4	8.7 ± 2	7.8 ± 2	8.7 ± 2	
Heavy metals ppb						
As	0.5 ± 0.2	0.6 ± 0.2	1 ± 0.4	0	2.2 ± 0.8	100
Hg	140.6 ± 50	115.7 ± 40	54.4 ± 10	55.6 ± 9	39.5 ± 20	100
Cd	2 ± 0.2	1.8 ± 0.1	1.9 ± 0.3	2.3 ± 0.4	2.2 ± 0.5	20
Ni	1.4 ± 0.4	3.3 ± 0.4	1.9 ± 1	4.9 ± 1	3 ± 1	10

3.2. Location and water source matters worldwide in reject brine mineral content

Seawater reject brines in general could be a predictable and reliable source of macronutrients if the mineral contents were similar and independent of facility location. Unfortunately, this is not the case between Spanish Mediterranean and Atlantic (Canary Islands) facilities (Table 1). Analysis of reject brines from the former showed a significantly higher content of three macronutrient ions. Specifically, Ca^{2+} and K^{+} were around 300 ppm higher, the differences being even higher for Mg^{2+} (by 500 ppm, Figure 4).

Figure 4. Macronutrient analyses of reject seawater brine from two desalination facilities in Spanish Mediterranean areas. A) Calcium, B) Magnesium, and C) Potassium concentrations from Alicante and Murcia desalination facilities, shown in blue and red respectively. Bars marked with the same letter show no statistical differences ($p < 0.05$).

That trend is found worldwide on analysing the data from various desalination facilities (Table 4). Published data showed a similar ion concentration in brine from facilities on Atlantic or Pacific coasts [60] and higher Ca^{2+} , K^{+} , Mg^{2+} ion levels in brine from those in the semi-closed Mediterranean Sea or the Persian Gulf [61,62]. This dependency on location is striking, especially on comparing seawater reject brines from desalination facilities only 500 km apart. The reject brine from Abu Dhabi in the Gulf had higher Ca^{2+} , K^{+} and Mg^{2+} levels than that from Muscat on the Indian Ocean, again showing the important influence of water bodies on brine composition. In contrast, those from facilities that use groundwaters as feed source were highly inconsistent in their contents. Calcium levels varied from 500 ppm to 2800 ppm, K^{+} from 32 ppm to 220 ppm and Mg^{2+} from 189 ppm to 7200 ppm.

Table 4: Reject brine macronutrient concentrations around the world.

Desalination facility						
Plant	Water source	Facility type	Ca^{2+} ppm	K^{+} ppm	Mg^{2+} ppm	Ref.
Tenerife ⁺	Seawater	RO	555.62 ± 20.81	864.7 ± 25.7	2090 ± 84.1	M
Alicante	Seawater	RO	849.7 ± 41.2	1069.6 ± 64.9	2659.7 ± 211	M

Murcia	Seawater	RO	787.7 ± 35	1061.7 ± 44.7	2575.3 ± 91.7	M
Australia	Seawater	RO	662	1220	2260	[60]
Abu Dhabi	Seawater	RO	760	950	2660	[62]
Muscat	Seawater	RO	625	668	1830	
Brazil	Groundwater	RO	1404	NS	1056	[28]
Israel	Groundwater	RO	959.4	70.4	378.5	
Bahja*	Groundwater	RO	1850 ± 98	220 ± 7.1	445 ± 21	
Rima*	Groundwater	RO	2850	152	670	
Nimr*	Groundwater	RO	1585 ± 106.6	141.5 ± 2.2	326 ± 25	[63]
Marmul*	Groundwater	RO	518.5 ± 4.9	32	189 ± 5.6	
Abu Dhabi	Groundwater	RO	202	84.5	510	[62]

+ Mean yearly average from the five studied brines; *means of two brines analysed; RO: means from reverse osmosis plant. NS: means data not shown. M: means measured in this study.

The data collected in Table 4 opens an interesting discussion about the need to properly regulate brine disposal into an almost closed water body like the Mediterranean. Its evaporation rate has increased by 20-30% over the period 1950-2010, which involves an 8 to 12% rise in salinity [64]. Researchers point out that the sea level is rising by between 0.03 and 0.3 mm/year in winter and about a third of this year-round [65]. Therefore, desalination facilities can continue using that sea as water resource, provided an integrated waste policy ensures a sustainable balance between environment and human activities [66]. Indeed, several long-term studies document negative impacts on benthic fauna, flora and algae near the brine discharge zone [17]. Environmental implications, followed by several associated problems that include closure of recreational facilities, noise and air pollution and aesthetic degradation are among the most usual reasons for this, often termed “Not In My Backyard (NIMBY)” [67]. One third of the Mediterranean population lives near the coastal regions, which involves an increase in activities such as tourism and agriculture, and consequently higher water consumption [68]. Nowadays, desalination is a costly water supply option for the Mediterranean regions [69], now requiring a technically and economically viable alternative that contributes to the sustainability of agriculture and water resources [70]. However, well-considered actions to reduce environmental impact and related rejection by local residents are the key to continuing water supply systems based on desalination in this and other low-rainfall regions.

3.3. Reject brine as a source of mineral salts for crops in hydroponic systems

The seawater reject brine was previously treated to produce the well-known Hoagland and Arnon solution [35] and later used as nutritive solution for a commercial fruit crop. This approach could be applied to a range of crops if the reject brine is adjusted with specific amendments, according to their respective nutritional requirements. Tables 5 and 6 show an example of the brine dilutions used to achieve the amendments needed for two profitable commercial crops (tomato and carnation), using reject brine values from three desalination facilities on Tenerife, and others in the Mediterranean, Australia and Abu Dhabi.

The specific nutritive solution for the tomato crop has a calculated conductivity near 3.2 dS/m, which is around 50% lower than in a previous study [30]. These conductivity differences between the optimised solution (Table 5) and those previously published depend on the higher mineral content of the Hoagland solution [71], which is reflected in much higher conductivity. Using a nutritive solution with high or low conductivity in this crop did not induce a notable variation in productivity [72]. However, high conductivity in the nutritive solution improves fruit firmness, colour and flavour [73]. In this regard, using brine to prepare the nutritive solution may reduce production costs by 14-20%, depending on its origin. Applying a modernised controlled hydroponic system like NFT where the solution circulates [72], crop yields can reach an average of 2.74 kg/plant [74]. These can reach higher productivities of 161.8 ± 6.6 ton per hectare, compared to 10.07 ± 0.4 in soil [75]. Furthermore, Spain operates more than half of all Europe's desalination capacity [76,77], which offers an excellent opportunity to install this procedure with the mentioned cost savings and better organoleptic features for Spain's horticultural produce. Implementation of reject brine use in hydroponic systems could become an exciting project to rescue this crop sector in territories like Spain, which has lost competitiveness compared to other producers in Europe and nearby [78].

Table 5. Optimised hydroponic solution for tomato cultivation with or without brine.

			Quantities of salts needed for 25L of stock solution with or without reject brine				
Salts			No brine	1/55 TF ¹	1/70 MED ¹	1/70 AUS ¹	1/70 AD ¹
Stock 1	Ca(NO ₃) ₂	(Kg)	2.16	1.01	1.00	0.6	0.60
	NH ₄ NO ₃	(g)	40	30	30	20	20
	KNO ₃	(g)	400	-	-	-	-

	Fe-EDDHA	(g)	34.9	12.78	17.45	10.4	9.61
Stock 2	MgSO ₄	(g)	950	-	-	-	-
	KH ₂ PO ₄	(g)	340	170	170	100	100
	KNO ₃	(g)	870	700	710	420	420
	K ₂ SO ₄	(g)	450	120	120	80	80
	H ₃ BO ₃	(g)	3.08	0.11	1.03	0.92	0.92
	CuSO ₄	(g)	0.62	1.58	0.31	0.19	0.19
	ZnSO ₄	(g)	3.6	1.58	1.80	1.08	1.08
	MnSO ₄	(g)	4.23	1.90	2.11	1.24	1.24
	(NH ₄) ₆ Mo ₇ O ₂₄	(mg)	440	-	220	130	130
Stock dilutions used			1:100	1:50	1:50	1:30	1:30
Expected conductivity (dS/m)			2.09	3.19	3.18	3.15	3.15
Nutritive solution cost (€ m³)			1.15	0.94	1.01	1.01	0.96

1. Amounts of salts were calculated using average mineral content of reject brines from desalination facilities at the specific locations. TF, Tenerife; MED, Mediterranean; AUS, Australia [60]; AD, Abu-Dhabi [62].

A similar approach could be used in the floriculture sector. Carnations are an important crop occupying more than 6000 ha [79] worldwide, and their hydroponic cultivation is not only viable [80] but an excellent alternative to conventional systems [81]. Previous studies confirmed excellent carnation production and quality using solutions with conductivities between 3-4.8 dS/m under continuous irrigation, without changes in flower weight or colour attributes [82,83]. The recommended solution (Table 6) using reject brine as a mineral source exhibits conductivity levels below 3 dS/m. These reduces costs by between 10-17%, depending on the precise brine composition. This opens up the possibility of utilising such brines as a mineral source in carnation production, in addition to more economical hydroponic systems in other horticultural and floricultural crops (Supplementary Tables 1 to 7).

Table 6. Optimised hydroponic solution for carnation cultivation with or without brine.

			Quantities of salts needed for 25L of stock solution with or without reject brine				
Salts			No brine	1/80 TF¹	1/70 MED¹	1/80 AUS¹	1/80 AD¹
Stock 1	Ca(NO ₃) ₂	(Kg)	1.89	0.9	0.86	0.53	0.53
	NH ₄ NO ₃	(g)	60	30	40	20	20
	KNO ₃	(g)	240	-	-	-	-
	Fe-EDDHA	(g)	58.25	26.6	20.13	17.48	17.48
Stock 2	MgSO ₄	(g)	760	40	-	10	-
	KH ₂ PO ₄	(g)	440	220	220	130	130
	KNO ₃	(g)	1030	680	710	410	420
	H ₃ BO ₃	(g)	4.63	1.33	1.8	1.39	1.39

CuSO ₄	(g)	0.62	-	0.31	0.19	0.19
ZnSO ₄	(g)	3.6	1.65	1.80	1.08	1.08
MnSO ₄	(g)	4.23	1.96	2.11	1.27	1.25
(NH ₄) ₆ Mo ₇ O ₂₄	(mg)	440	-	220	130	130
Stock dilutions used		1:100	1:50	1:50	1:30	1:30
Expected conductivity (dS/m)		1.78	2.58	3.02	2.97	2.8
Nutritive solution cost (€ m³)		1.18	1.05	1.09	1.1	1.09

1. Amounts of salts were calculated using average mineral content of reject brines from desalination facilities at the specific locations. TF, Tenerife; MED, Mediterranean; AUS, Australia [60]; AD, Abu-Dhabi [62].

3.4. Economic study of using reject brine in a soilless tomato plantation

The present research line has already highlighted the benefits of reject brine use in small-scale laboratory hydroponic systems [30]. However, no studies or estimates for reject brine use in a typical greenhouse hydroponic facility have been examined. In the Canary Islands, a 2 ha hydroponic tomato crop greenhouse could have two harvests per year and a building cost between 25 to 84 €/m² [84]. This needs an opening investment of €1,080,000. Furthermore, considering the production costs and incomes per year and the NFT hydroponic system running costs, the farmer would need eleven years to recover the opening investment (Table 7).

Table 7. Reject brine implementation study

Two-hectare tomato production costs				
Concept	Without		With	
	brine		brine	
	€/m ²	Two season cost	€/m ²	Two season cost
Water used	0.15	6,000	0.15	6,000
Fertiliser	0.46	18,400	0.36	14,400
Other cost (Plants, Pesticides, Labour, Energy, etc.)	4.41	176,400	4.41	176,400
Total cost	5.02	200,800	4.77	190,800
Income €/m ²	7.48	299,200	7.48	299,200
Net income	2.46	98,400	2.71	102,400
Years to recover initial investment		11		10.5

Previous studies demonstrate how reject brine could diminish fertilisation costs by 21% using 1/55 dilution without any productivity losses [72]. That means an extra income of 4000€ per year, being 4% more profit, reducing the pay-off period by six months. For comparison, it is interesting that tomato production in soil produces a yearly net income of 13,797 € per hectare in the Spanish Mediterranean [85], much less in countries like Turkey: 1,592 to 2,218 € [86]. However, recent studies point out that in some regions of Spain most of the producers worked at

a loss [87]. This highlights the importance of moving towards improved systems such as hydroponics, and brine reutilisation can help with this transition.

Beyond the direct savings in fertilisation, reject brines bring opportunities to increase profits. One option is to use brine as a new source of freshwater. A short-cut approach to minimise energy costs is the capture and direct utilisation of solar energy to evaporate the brine and obtain water. In the bibliography there are descriptions of several alternative techniques (for an extensive review see [88]). One problem affecting this kind of evaporator is final production price of water, to save enough on its maintenance cost and to recuperate the initial investment in the evaporator. This may be on average from 0.023 €/L [89], reaching unaffordable water prices for the producers. Another problem is that most of these systems are optimised for seawater, not for brine, in which the high evaporation rate needed to maintain water output cannot be maintained [90] due to high salinity. In this regard, new materials used as surface covers can keep or increase evaporation rates [90–93], which presents an interesting field for optimisation to use brine as water source for agricultural fields.

In this context, a promising commercial evaporator is the SunAqua-18 [94] system designed by aqua-abib®. It consists of a pyramid-shaped structure with an octagonal base, measuring 18 m in height, covering an area of 2,500 m². This technology harvests sunlight with 70% efficiency, heating the air between two plastic layers and the vapour naturally rises to the top of the pyramid surpassing 100 °C [95]. According to the development team, the equipment can produce 25,000 m³ of freshwater using desalination reject brine as supply source [94], with a low energy consumption. This volume is well above the 6,000 m³ needed by the Hydroponic Nutrient Film Technique (NFT) system in continuous production with two harvests per year. This could provide extra revenue selling the surplus freshwater. Indeed, the average price for desalinated water in Spain is 0.6 €/m³, giving an extra 11,400 €. However, the final viability must consider the time to pay off the investment in the evaporator, and its running costs (precise figures are currently unavailable).

Another method to obtain revenues from rejected brine worth exploring is to couple evaporation with precipitation protocols. An interesting study [63] proposes treatment options to apply reverse osmosis to reject brine. The simplest process produces substantial amounts of sodium

chloride and gypsum, with a market price of 8.2 and 7.1 € per tonne respectively [96], and also other more valuable compounds such as magnesium hydroxide, used to obtain the pure magnesium oxide widely used for pharmaceutical and semiconductor purposes [97]. An interesting review [98] is focused on the processes necessary to obtain these and other elements from reject brine. Altogether, excellent avenues for further research into these techniques are foreseeable, applying circularity paradigms to increase secondary income.

4. Conclusions

Desalination is probably one of the fundamental technologies capable of solving the world water scarcity problem. However, managing the seawater reject brine produced during the process is a significant concern preventing this technology from expanding worldwide.

This one-year study shows how this brine could be an excellent source of valuable macronutrients. Specific minerals were found in constant reliable high concentrations (Ca^{2+} , K^{+} and Mg^{2+} , SO_4^{4-} and B^{-}) during the analyses, independently of the facility location.

Brine implementation in an hydroponic cultivation is rentable, due the reduction in crop production costs due to using less fertiliser, producing an extra revenue of 4000 € per year. This shortens the payback time by six months. Data available from desalination facilities worldwide confirm how this system can be used to provide similar reductions in running costs in a plethora of commercial horticultural and floricultural crops.

Utilisation of freshwater produced from brine with a proper evaporation system has the potential to generate extra revenue of €17,400 (€6,000 from water input cost savings + €11,400 by selling the surplus fresh water generated). This income could also be increased by selling or using the salts obtained after brine evaporation. In any case, appropriate research has still to be done to more reliably estimate the total potential profit, and amortisation time required to recuperate investment in the new infrastructure.

Finally, this system based on a raw material such as brine allows the general public to visualise and understand the opportunities for applying desalination technologies beyond fresh water generation, thus promoting wider acceptance of this technology. With an optimised design, implementation of such a set-up not only increases profitable food production, it also shows a way to reach beyond the current semi-sustainable desalination facilities.

Author contribution statement

David Jiménez-Arias: Conceptualisation, Research and Data curation; Sarai Morales-Sierra: Research; Francisco J. García-Machado: Research; Ana L. García-García: Research; Juan C. Luis: Writing - Original Draft; Andrés A. Borges: Funding acquisition, Supervision.

Declaration of competing 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.

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