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Experiences of desalination for agriculture in Spain: technology, economy and innovation

Patricia Terrero*, Domingo Zarzo

Innovation and Strategic Projects Department, Sacyr Agua, Spain, Phone: +34 915455000; emails: pterrero@sacyr.com (P. Terrero), dzarzo@sacyr.com (D. Zarzo)

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ABSTRACT

Food security is one of the main challenges for the future. Expectations from UN indicate that it is necessary to double food production in the next years. This means that water needs will grow more than expected and the use of the non-conventional water resources will be absolutely crucial. Desalination for agriculture is almost irrelevant globally, although countries such as Spain have demonstrated that desalination can be used for supplying an agriculture based on high added value crops. In this paper we will analyze this application with the experiences and knowledge acquired in the last years, including the history of desalination for agriculture, technical and economic aspects, success stories and innovation. It is also remarkable that farmers from the Southeast of Spain (Mediterranean Coast) have established a very efficient irrigation system which is fed by a blending of water from different origins obtaining in this way a good quality water with affordable prices. In the field of innovation, 2 main projects related with agriculture will be shown; LIFE DESEACROP, which was developed to demonstrated the feasibility of the use of desalinated water for agriculture and SOS-AGUA-XXI, a 6 Million € R&D project funded by Spanish Government with European Funds.

Keywords: Desalination; Agriculture; Boron

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1. Introduction

Water is a valuable and very scarce resource. Drought and the effects of climate change threaten a large part of the world's population (800 million people do not have access to drinking water and 3.6 billion do not have sanitation), and they also generate disasters such as floods and torrential rain.

On the other hand, the growth of the world's population will make it necessary to double food production by 2050, according to the United Nations, being agriculture the largest consumer of water worldwide (70%).

In this situation of water scarcity, it is necessary to look for other water resources, such as the so-called unconventional ones (desalination and reuse), to satisfy the growing demands of the population and food production.

While the use of desalinated water for agriculture is a virtually irrelevant activity worldwide, accounting for no more than 2% of total uses [1], Spain is a rarity in this sense, being the country of greatest use for this application, with values above 21% [2].

In Spain, the structural water deficit has led farmers in Eastern Spain to have desalination as part of their water resources, integrating surface waters from transfers, groundwater, reused water and desalinated water (brackish and sea), thus obtaining a reasonable price thanks to the blending of all these contributions. In addition, the high investment returns of greenhouse crops, highly technician with off-season products, make the cost of desalinated water affordable within the production costs for this sector of high quality products. We must also stress that it has been scientifically demonstrated (in R&D projects such as LIFE DESEACROP,

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* Corresponding author.

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led Sacyr Agua) that the use of desalinated water for agriculture increases productivity and crop quality.

Likewise, reclaimed water has been used in municipal, industrial or agricultural uses. To be able to offer this second use to water it is necessary to apply an additional treatment to the conventional treatment of purification (known as tertiary treatment), which may be more or less complex depending on the quality of purified water, the use for which the water is to be used and the requirements from the regulation in the country.

2. Desalination for agriculture in Spain

2.1. History of desalination and desalination in Spain

Desalination has much older origins than is usually thought; the first historical references go back to Aristotle or Pliny the Elder, who already developed studies on desalination and the Egyptian alchemists, that used stills for distillation. Later the Roman Legions used solar evaporation to supply themselves with water in their campaigns in Africa, storing water in shallow ponds (solar ponds) from which condensed water was subsequently collected.

The Vikings also used the technology of "fog catchers", using the sails of ships to collect dew or humidity during their boat trips. This technology is still used in some desert areas and can still be seen in the Andean Cordillera.

In Spain, many of the scientific advances of the Arabs, who also experimented with stills, came through universities, such as Toledo, including distillation and evaporation technologies [3]. Subsequently there are numerous references of water production on ships between the fifteenth and seventeenth centuries, by means of rudimentary devices (distillers powered by firewood or coal) until the arrival of the industrial revolution, with the development of the steam engine, introduced evaporative desalination on ships in a more technological way, which was later extended to industrial applications and small desalination plants.

The use of membranes is relatively recent; in 1748 the French ecclesiastic and physicist Jean Antoine Nollet studied the passage of water through semipermeable membranes and some years later Henri Dutrochet, French physician, biologist and physiologist, discovered the osmosis process. None of these studies resulted in practical applications (and remained almost as laboratory curiosities) until the 1960s, when researchers Sydney Loeb and Srinivasa Sourirajan developed in California the first flat cellulose acetate reverse osmosis membranes, opening the way to the development of commercial membranes that had their development on a large scale since the 80's.

In Spain, the first desalination plant "on land" was a small seawater evaporation desalination plant built in Lanzarote in 1964. This was the beginning of the development of desalination in the Canary Islands (and in Europe), which would later jump to the Balearic Islands and finally to the Iberian Peninsula.

In the 1970s various plants were installed in the Canary Islands, first for hotels and tourist and leisure areas and after it in the 1980s for agriculture, including reverse osmosis technologies (seawater and brackish) and electrodialysis reversal (for brackish and wastewater), due to the high content of silica in the island's groundwater.

In the 1980s, some drinking water plants began to be built on the Iberian Peninsula, including seawater and brackish water plants, which were gradually growing in size.

In the provinces of Almería, Murcia and Alicante, with the severe drought of the 90s, about 300 units of private plants were installed for small production agriculture (500–5,000 m^3/d) [2]. At that time, agriculture was extremely dependent on river water transfers, and with the drought, alternatives such as desalination and reuse were sought for the sector's survival. In general, these plants were desalination brackish groundwater plants, although some seawater plants were installed in the Canary Islands. Most of these facilities were built with reverse osmosis technology, although in the Canary Islands around 20 plants of electrodialysis reversal were built, with sizes between 1,000–5,000 m^3/d [2]. The farmers of the Spanish Levant continued to increase desalination capacity until they built plants of significant size, such as those owned by the Communities of Irrigation end users of Cuevas de Almanzora, Mazarrón or Rambla Morales.

Between 2004 and 2011 the Spanish government (through the Ministry of Environment, currently called Ministry of Ecological Transition and Demographic Challenge) developed the AGUA program, in order to implement a number of desalination projects (about 25 plants with capacity production close to 700 Hm^3/y) on the Mediterranean coast to face the region's water deficit as opposed to the policy of river transfers promoted by previous governments. This led to a huge increase in desalination to the current installed capacity, estimated at around 5 million·m^3/d, which, if fully allocated to the production of drinking water, could supply a population of 34 million people [4]. It is currently estimated that in Spain there are more than 770 desalination plants over 100 m^3/d, with more than 100 over 10,000 m^3/d [4]. The largest seawater desalination plants in Spain are SWRO Plant Torrevieja (240,000 m^3/d) and SWRO Plant Aguilas (210,000 m^3/d) and in the case of brackish water, the largest plants are BWRO El Atabal, in Malaga (200,000 m^3/d) and EDR Abrera, in Barcelona (200,000 m^3/d), which is also the world's largest plant with reversible electrodialysis technology.

Most large desalination plants are currently in operation, although not all of them at full capacity. Some facilities, such as SWRO Aguilas, have important agreements with agriculture end users that guarantee their operation with a very high percentage of productivity (basically destined to agriculture, for the Communities of end users of Lorca, Pulpí and Aguilas), but others, such as those of Muchamiel, Sagunto, Oropesa or Moncofar, producing drinking water, are currently underutilized. Table 1 shows the last published data about the status of the largest desalination plants in Spain managed by Acuamed [5].

In addition to the large desalination plants managed by Acuamed, we must also consider as relevant, since they represent important capacity, the SWRO desalination plants of Alicante and San Pedro del Pinatar owned by Canales del Taibilla (Public Company depending on the Ministry), and the desalination plants in the Canary and Balearic Islands, Ceuta and Melilla, managed by the governments of these regions.

Table 1
Current situation of large seawater desalination plants in Acuamed (except *Atabal, which is brackish water) in Spain

Desalination plant	Hydrological basin	Province	Production capacity (Hm^3/y)	Production state
Oropesa	Jucar	Castellón	18	Operation without production
Moncofar	Jucar	Castellón	10	Operation with
Sagunto	Jucar	Valencia	8	Explotación sin hout production
Mutxamel	Jucar	Alicante	18	In operation
Torrevieja	Segura	Alicante	40/80	In operation
Valdelentisco	Segura	Murcia	48	In operation
Aguilas	Segura	Murcia	60	In operation
Bajo Almanzora	Sur	Almería	0/15	Into rehab.
Carboneras	Sur	Almería	42	In operation
Campo de Dalías	Sur	Almería	30	In operation
Marbella	Sur	Malaga	20	In operation
*Atabal	Sur	Malaga	60	In operation
Total			354/394/409	

As expected, the distribution of desalinated water in the different river basins (and therefore in the different regions of Spain) is very different. For the period 2012–2015 there were 159 Hm^3/y produced in the Segura basin, 129 Hm^3/y in the Canary Islands, 44 Hm^3/y in the Andalusian Mediterranean basins, 35 Hm^3/y in the Jucar, 28 Hm^3/y in the Balearic Islands, 17 Hm^3/y in the internal basins of Catalonia, 8 Hm^3/y in Melilla and 7 Hm^3/y in Ceuta [6].

Most of the small desalination plants built by irrigation communities or private farmers in the 1990s are currently out of operation due to various reasons (lack of permits, problems with brine management, etc.) but in recent years groups of agricultural entrepreneurs from the provinces of Murcia and Almería are planning to plan several large seawater desalination plants of their own to reduce their dependence on water transfers.

Apart from seawater installations, it is noteworthy the growing implementation of desalination membranes for the improvement of surface waters (even in large plants, such as the River Tajo DWTP, BRWO El Atabal and EDR Abrera) and also for tertiary wastewater treatment (such as the Rincon de León WWTP in Alicante or the Benidorm WWTP).

2.2. Desalination for agriculture in Spain

In Spain, the structural water deficit has led the irrigation communities and agricultural enterprises of the Spanish Levant to have desalination as part of their water resources, integrating surface waters from transfers, groundwater, reused water and desalinated water (brackish and sea), thus obtaining a reasonable price thanks to the mixture of all these inputs.

We must also stress that it has been demonstrated that the use of desalinated water for agriculture increases the productivity and quality of products. For example, in an unpublished 1997 study, we observed that replacing the groundwater used up to that time with desalinated water increased the production for oranges of the Navel variety between values of 10% to 50%, further reducing the amount of water required by 20%. Also, the research project LIFE DESEACROP has demonstrated the highest production and quality of agricultural products irrigated with desalinated water, in this case in crops without soil (hydroponics).

Desalination for agriculture has a number of peculiarities that make it different from application to other uses, such as its lower requirements in water quality and post-treatment, in labor, chemicals and membrane replacement, ability to regulate production thanks to storage systems (thus being able to take advantage of more favorable electricity rates) and simplicity. These measures therefore make it possible to obtain lower costs than plants designed to produce drinking water for supply (which must also have additional safety measures).

Against all the advantages of desalination for agriculture there are also some drawbacks (in this case of chemical origin), such as the presence of boron in seawater (and to a lesser extent in the water product) which is toxic to some crops, and the elimination of which involves extra costs, as well as the chemical imbalance of the water, represented by the SAR (sodium absorption ratio), which, if high (as in desalinated waters without remineralization) implies a risk of waterproofing of the soils. In general, both problems are solved in the case of agricultural application by means of the mixture of waters of different origins, further reducing the overall cost of the water produced. In Table 2, we can see the different contributions and prices of water corresponding to a Irrigation Community in the province of Almería, including the supply of desalinated water, which reflects this strategy of mixing to reduce costs and improve remineralization.

In Table 3 we can see the great growth that has had the use of desalinated water for agriculture in recent years. Although it is only the production of the large seawater desalination plants of Acuamed (not considering other private plants owned by the agricultural sector or other public plants owned by other public companies), it gives us an idea of the magnitude and growth of this application (and with agriculture being the main consumer since 2015).

According to the data in Table 3, Acuamed plants have produced a total of 1,426 Hm^3 of desalinated water from the

Table 2
Supply rights, prices and water mixes in a community of irrigators in Almería

Water source	Supply rights (Hm^3/y)	Water conductivity (mS/cm)	Water price (€/m^3)
Tajo-Segura rivers transfer	5.32	2,000	0.11
Negratin river transfer	5	1,300	0.23
Subtotal	10.32	1,661	0.17
Groundwater wells	1.5	3,500	0.09
Desalinated water	4.5	300	0.34
Subtotal with desalinated water	16,32	1.455	0.21

Source: own elaboration

Table 3
Production of desalinated water from large Acuamed desalination plants in the Spanish Mediterranean (in Hm^3/y and %) for different uses

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
D	0.00	10.06	49.21	49.67	54.46	59.50	47.67	45.14	50.99	42.56	51.72	52.17	64.70	93.08	103.7
%	0	93.1	95.0	95.0	93.4	88.5	77.8	71.8	70.5	51.6	51.2	38.9	33.5	39.3	42.9
A	0.00	0.53	2.27	2.42	3.54	7.37	13.16	17.28	19.02	37.47	47.30	**79.56**	**125.6**	**141.5**	**135.8**
%	0	4.9	4.4	4.4	6.1	11.0	21.5	27.5	26.3	45.4	46.8	**59.4**	**65.1**	**59.7**	**56.1**
I	0.00	0.20	0.29	0.25	0.31	0.37	0.50	0.53	2.25	2.49	2.09	2.53	2.47	2.81	2.14
%	0	1.9	0.6	0.48	0.53	0.55	0.82	0.84	3.1	3.0	2.1	1.9	1.3	1.2	0.9
T	0.00	10.8	51.8	52.3	58.3	67.2	61.3	62.9	72.3	82.5	101	134	193	237	242

Source: adapted from [5] (D = drinking water, A = agriculture, I = industry, T = Total).

Table 4
Water productivity for different crops in the Segura basin (Spain)

Crop	Yield (kg/ha·y)	Total water footprint (L/kg)	Price (€/kg)	Economic productivity of land (€/ha·y)	Economic productivity of water (€/m^3)
Rice	4,950	2,283	0.3	1,318	0.15
Potato	33,600	199	0.2	7,716	1.98
Lucerne	70,000	121	0.1	9,691	1.15
Horticultural greenhouse crops	85,000	80	0.6	48,531	6.97
Horticultural outdoor crops	37,000	199	0.4	14,536	3.11
Fleshy fruits	21,000	350	0.5	11,444	2.48
Cotton	2,000	4,321	0.3	721	0.17
Citrus	30,000	257	0.2	7,000	1.38
Almonds	1,100	4,454	1.0	1,112	0.51
Vineyards wine/table grapes	3,600/25,000	1,073/247	0.6/0.6	2,067/14,999	1.64/3.99
Olive trees	7,600	485	0.5	3,905	3.90

Source: adapted by the study of Aldaya et al. [7].

beginning of the implementation of the program in 2005 (until 2018), representing agricultural use 43% of this production. This proportion has been growing (and continues to grow) and in 2018 already accounted for 55%.

The general opinion, and that of the farmers themselves who use desalinated water, is that desalinated water is expensive. Indeed, it is clear that only certain products can be allowed to use desalinated water as the sole source of supply (for the price of the product and the percentage of water in their production costs) and there are some products for which it would be totally unfeasible. Taking into account the costs of desalinated water previously exposed, it is interesting to observe the water productivity for different crops (Table 4), studied in the Segura basin [7] where we can see that some crops have a very high productivity of each m^3 of water, being able to afford the use of a higher price water, such as desalination.

The economic productivity of water represents the economic yield we get for each m^3 of water supplied, so those products with productivity values above 1 €/m^3, could theoretically afford the price of desalinated water from the sea, and those above 0.3 could bear the price of brackish desalinated water.

This could also have future influence on trends in the agricultural production market in the area, taking into account product prices and water productivity and availability. According to the aforementioned report [7] in the Segura basin, the crops with the highest water consumption are in this order; citrus fruits (35%), open-air vegetables (32%) and fruits (17%), with average productivity (1.4, 3 and 2.5 €/m^3, respectively). These crops together represent 3.5 times more water consumption than the rest of the crops. Horticultural greenhouse (tomatoes, lettuce, etc.) consume only 5% of the water in this basin, and having the highest economic productivity (7 €/m^3), they only represent 3% of irrigated agriculture and 14% of the economic value of the irrigated area.

The main limitation for the widespread use of desalinated water for irrigation purposes is the high final price of this resource. Currently, the cost of seawater desalinated water production ranges between 0.35–0.5 €/m^3 (0.6–0.8 €/m^3 with amortization), depending on plant size, type and distance uptake and distance to the distribution point. In brackish water desalination, this value is around 0.15–0.3 €/m^3. Although this cost can be considered high, the water cost share in a typical agricultural holding in Almeria represents only about 3% of the total production cost [8].

Desalination costs vastly vary depending on the size and type of the desalination plant, the source and quality of incoming feed water, pre-treatment requirements, automation and control, the plant's location, site conditions, qualified labor, energy costs and the plant's lifetime [9].

As we see, the price of water is always the determining factor when using desalinated water, provided that other sources are not available cheaper, since these are always the first to use (This is also the case with the supply of drinking water, which is why public plants are underused). In a study conducted on different surveys to irrigators in the Campo de Níjar (Almería) [10], it was observed that the most important measures to promote desalinated water in agriculture in the area, according to users, would be, in this order, subsidies and discounts on prices, reduction of taxes or volumes and finally an information campaign on their profits.

Desalinated water for agriculture has sometimes been subsidised by the administration, supplying desalinated water below its cost of production (which would be contrary to the European Water Framework Directive and cost recovery). For example, in Campo de Cartagena (agriculture region in Murcia province), irrigators paid for water in the period from October 2015 to April 2016 at 0.36–0.39 €/m^3, whereas in the previous semester they paid 0.14–0.17 €/m^3 (water from other sources) due in the first case to the use of subsidized desalinated water (Martinez et al., 2016). The authors also indicate in the article that, if this subsidy had not been available, the price could have been around €0.65/m^3, which could not have supported all crops.

We should also note that the use of desalinated water for agriculture in Spain has attracted the attention of many other countries interested in this application and there have been numerous international delegations visiting various desalination plants and irrigation. An example of these countries is Australia, where feasibility studies have been carried out and where some projects are already under way [9].

3. New trends and research and development in desalination for agriculture

All these achievements in technology and water supply through unconventional resources would not be possible without the development of innovation in our companies, administrations and research centers, also world leaders in the water sector. Innovation is an essential tool in the development of these technologies; new trends in innovation in water are always oriented towards increasing sustainability; as recovery of valuable components of wastewater or brines (brine mining) circular economy, increased efficiency and use of renewable energy or digital transformation.

In this paragraph we will describe some Innovation projects related to desalination for agriculture such as:

- LIFE Desacrop, funded by the European LIFE Programme, to develop desalination for sustainable agriculture, including the recovery of agricultural drains. https://www.deseacrop.eu
- Project SOS-AGUA-Misiones, financed by CDTI with Next Generation Funds, which studies different future solutions for water supply for agriculture including digitization projects, predictive models of water and energy consumption, renewable energy solutions and green hydrogen, etc.

Besides other innovation projects related to desalination and which can have impact over desalination for agriculture (although they will be not described in detail in this paper).

- LIFE Transfomem project, funded by the European LIFE programme, to develop the transformation of used reverse osmosis membranes into nanofiltration membranes (NF), microfiltration (MF) or ultrafiltration (UF) for other applications (wastewater treatment, water for agriculture, etc.). https://www.life-transfomem.eu
- LIFE Hyreward project, funded by the European LIFE programme, which aims to produce energy by harnessing the saline gradient between a desalination

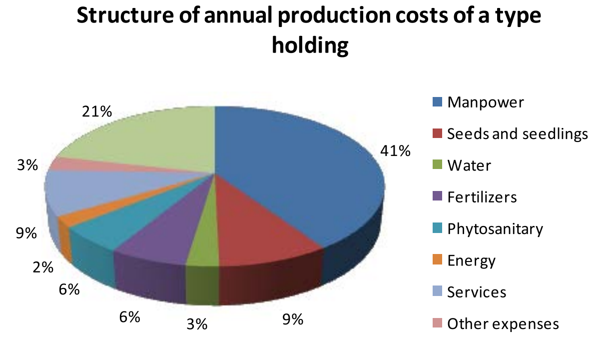

Fig. 1. Structure of the annual production costs of a type holding. Adapted from [8].

concentrate and a freshwater stream through the application of reverse electrodialysis. https://life-hyreward.com
- Energy recovery project for desalination plants using a solar-powered steam-water pressure exchanger (financed by CDTI).
- Project CAPTA (Advanced Center for Water Technologies) funded by Corfo in Chile, for the development of new sustainable solutions for desalination in Chile, including studies on the environmental assessment of desalination plants and desalination for agriculture. https://www.centrocapta.cl

3.1. LIFE DESEACROP

In this section we will describe the European project LIFE DESEACROP (LIFE16 ENV/ES/000341), which aimed to demonstrate the sustainable management of desalinated seawater for crop production in closed soilless systems with the final goal of strengthening resilience of these systems as a key productive, economic, social and environmentally friendly sector in water-stressed regions.

A greenhouse test was carried out to compare cropping in soil and soilless cropping and demonstrate the viability of soilless systems to grow vegetable crops and of using re-mineralized DSW for irrigation, as a sustainable and environmentally friendly strategy. Tomatoes have been employed as the main crop in the comparison, due to the fact that they are the most significant crop in the region. 4 short Canary red tomato cultivation cycles were realized with an approximate duration of 5 months each.

The demo plot (Fig. 2) was located in the test farm of the Foundation Experimental Farm of the University of Almería – ANECOOP Foundation. The test greenhouse has a total surface area of 1,454 m^2, divided in 18 test plots, where three treatments have been applied with three repetitions in cropping in soil and three treatments with three repetitions in a soilless cultivation plot. For each plot, three different irrigation treatments have been performed: T1: precision irrigation with DSW (ECw around 0.5 dS/cm), T3: precision irrigation with synthetic groundwater (ECw around 3.0 dS/cm), and T2: precision irrigation with a synthetic mixture of water at 50% coming from both resources (ECw around 1.5 dS/cm). Table 5 shows the chemical characterization of irrigation water and fertigation.

In the case of soilless cultivation plot, drainages have been treated by a solar-assisted desalination plant to reuse the treated water again for irrigation. The drainage treatment plant, in a transportable container, is composed of pre-treatment with recycled UF membranes, and a reverse osmosis system, all of this powered by photovoltaic solar energy.

3.1.1. Experimental study in tomato cultivation. Comparison of crops in soil and soilless systems and evaluation of drainage treatment

During the project, 4 crop cycles were carried out, and the results (Figs. 3 and 4) show a clear advantage in the use of DSW in soilless system.

The results of the experimentation work showed a higher production of tomato per greenhouse surface (kg/ha) in the soilless or hydroponic system (HS) compared with soil

Fig. 2. Demonstrative plot used in the LIFE DESEACROP project.

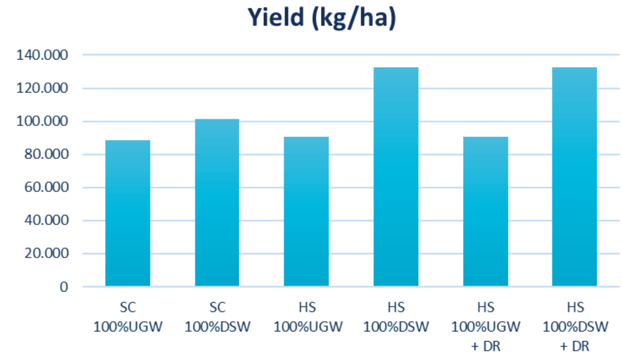

Fig. 3. Crop yield comparison in each treatment.

Table 5
Chemical characterization of irrigation water and fertigation for the three treatments

	(me/L)	NO_3^-	$H_2PO_4^-$	SO_4^{2-}	HCO_3^-	Cl^-	NH_4^+	K^+	Ca^{2+}	Mg^{2+}	Na^+	ECw (dS/m)
T1	Irrigation water	0.01	0.00	0.12	0.83	3.66	0.00	0.09	0.64	0.36	3.48	0.50
	Water + fertilizers	12.61	2.10	2.62	0.87	3.85	0.53	7.84	7.88	2.10	3.66	2.20
T2	Irrigation water	0.01	0.00	2.92	3.64	5.31	0.00	0.09	6.26	3.16	5.13	1.50
	Water + fertilizers	11.62	1.94	5.13	3.52	5.13	0.49	7.22	12.69	4.65	4.96	3.00
T3	Irrigation water	0.01	0.00	7.12	7.85	7.77	0.00	0.09	14.68	7.36	7.59	3.00
	Water + fertilizers	11.64	2.07	6.14	6.76	6.70	0.43	9.04	12.64	6.35	6.54	3.50

cultivation (SC). However, they made less efficient use of water (m^3/ha) and presented with lower productivity. This has been offset by the treatment and reuse of the drainage, which has generated a saving of 20% in water consumption.

Comparing the results obtained with the different types of water, irrigation with DSW increased the production of SC by 14% and up to 46% in the case of HS, compared to irrigation with underground water (UGW).

Other important results revealed a more efficient use of fertilizers in treatments with lower salinity waters (T1), a lower sugar content (Brix degrees) related to ripening and degree of sweetness, and an absence of damage to growth of plants (Phyto-toxicity).

Regarding the drainage treatment, this consists of a pretreatment with recycled UF membranes (developed by Sacyr Agua within the Life Transfomem project) and a reverse osmosis.

Table 6 shows the average composition of the drainages during the treatment, observing the way the quality of the treated water obtained represents excellent quality for its reuse in agricultural irrigation. During the experimentation, thanks to the designed drainage treatment system, a recovery of the water from the drainages of up to 64% has been achieved, for reuse in agricultural irrigation, reducing the overall crop water consumption.

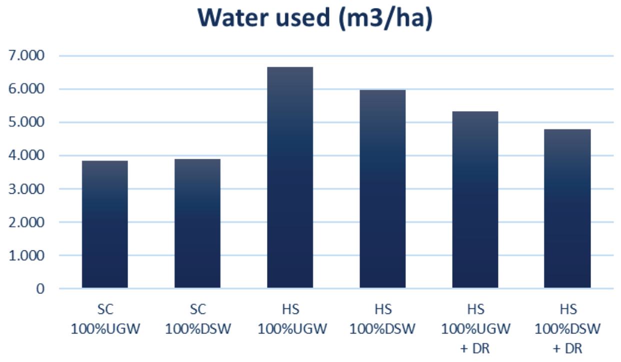

Fig. 4. Water used comparison in each treatment.

Table 6
Average drainage composition during the treatment

	Drainages	Ultrafiltered drainages	Treated water
pH	7.01	7.65	6.18
CE (dS/m)	6.21	4.93	0.15
Cl^- (ppm)	1,473.59	1,029.07	33.13
NO_3^- (ppm)	88.33	40.00	7.22
SO_4^{2-} (ppm)	915.70	684.49	14.34
HPO_4^{2-} (ppm)	43.97	23.17	5.19
Na^+ (ppm)	622.21	426.68	17.65
Mg^{2+} (ppm)	187.43	115.00	0.96
K^+ (ppm)	85.73	103.23	4.99
Ca^{2+} (ppm)	418.95	213.93	1.96
B (ppb)	3,124.11	2,255.79	1,416.38
Mn (ppb)	20.77	13.91	0.00
Fe (ppb)	22.74	18.37	0.00
Cu (ppb)	25.80	26.82	0.00
Zn (ppb)	30.71	27.72	7.06

3.2. SOS-AGUA-XXI

Guaranteeing the quality and quantity of water resources is the biggest challenge facing the Spanish agricultural sector. The progressive scarcity of conventional water resources, the effects of climate change and the increase in demand for food production expected in the next 20–30 y, it is essential to develop a modern and efficient agriculture in the consumption of water and energy, as well as the promotion and development of the use of non-conventional water resources, such as desalination and reuse.

For this reason, the Innovation and Strategic projects Department at Sacyr Agua is currently developing a large Research project called SOS-AGUA-XXI, funded by the Spanish CDTI with European Next Generation funds.

The project, lead by Sacyr Agua, is proposed to the Mision "XXI Century Agriculture", covering all the call objectives such as digitalization, water quality for agriculture, recovery of nutrients from water from different origins and sludge, energy efficiency, as well as sustainability and economic and social impact of the activities.

The consortium of the project is formed by companies of different sizes and profiles including SACYR AGUA, VALORIZA SERVICIOS MEDIOAMBIENTALES, BOSONIT, TEPRO, REGENERA, AEROMEDIA, föra y AQUA ADVISE, besides an important number of Spanish Research Centers and Universities: Water and Environmental Sciences Institute from the University of Alicante (IUACA), University of Salamanca (USAL), Polytechnic University of Cartagena (UPCT), Chemical Engineering Department from University of Alicante (UA), mixed group of economy from the Universities of Alicante and Alcalá de Henares (UA-UAH) and a Technological Centre linked to Universidad de Sevilla (AICIA).

The project began in 2021 and with a duration of 3 y and 3 months and a budget of €6 Million, has as the main objective to research about technological solutions that, having the focus on sustainability and energy efficiency, allow strategies to be developed for the efficient management and treatment of the water resources for the agriculture sector. All this makes it possible to guarantee the quality and quantity of water resources, as well as to adapt and prepare the Spanish agricultural sector to fight against the progressive scarcity of conventional water resources and the effects of climate change.

3.2.1. Research lines

The SOS-AGUA-XXI project has a total of 35 research lines or tasks that are included in the following activities:

Activity 1: Theoretical and conceptual definition of sustainable impulse technology solutions for agriculture.

Activity 2: Laboratory scale experimental research of technological solutions.

Activity 3: Advanced analysis of variables involved in water resources management and generation of algorithms and models.

Activity 4: Pilot-scale research of the technological proposals.

Activity 5: Development of ICT solutions applied to the improvement of water resources.

Activity 6: Evaluation and validation of the solutions over use cases

The project includes inside these research lines, activities such as studies of effect of boron from desalinated plants over crops and soils, recovery of nutrients and salts from brines and drainage water (by microalgae and brine mining), submarine and aerial drones, production of green hydrogen with reclaimed water, predictive models of water and energy consumption, determination and treatment of compounds of emerging concern in reclaimed water for agriculture, predictive models of events of extreme weather and their effects over agriculture infrastructures, economical and social impact, etc.

In this paper we will describe the current advance of one of the main research lines in SOS-AGUA-XXI related to the improvement of water quality for agriculture, studying the effect and presence of boron in crop and solid from desalination plants.

3.2.2. Study of the agricultural impacts of irrigation with desalinated seawater and high boron content

Continued water scarcity in the Segura River basin in Spain has led to the use of unconventional resources, such as seawater desalination and the reuse of wastewater, which are now an important source of supply for irrigated agriculture. The availability of these resources has been essential in order to maintain the necessary allocations for irrigation in the last decade, having become the most important part of the waters provided in some coastal areas. However, these waters have special characteristics in their physico-chemical composition, which differentiate them from natural waters, and which must be known and controlled to avoid possible adverse agronomic effects.

One of these singularities, which could affect its use in irrigation, is the high concentration of boron (B), both in regenerated water [11] and desalinated water [12,13].

In agriculture, boron (B) is an essential trace element for the growth, development and productivity of fruit and vegetable crops. Its availability in soil and irrigation water is an important factor in agricultural production. However, there is a very fine barrier between the concentration at which it is suitable and that it can be toxic to crops [13].

The concentrations of B in surface irrigation water are generally less than 0.1 mg/L, so complementary inputs in the form of fertilizers (through micronutrient complexes) are usually necessary for the correct development of crops. However, unconventional water resources (regenerated water and desalinated marine water (AMD)) are characterized by concentrations of B significantly higher than surface water, it is common to find values around 1 mg/L. These concentrations satisfy the needs of the crops, and could even lead to phytotoxicity in the case of the most sensitive crops, affecting their correct vegetative development and, consequently, to its productivity. Increasing values in the concentration of B intensify phytotoxic effects, which can produce more critical effects such as permanent wilting of the crop or soil contamination.

In order to evaluate the effects of boron on crops, as well as the economic evaluation of the cost of eliminating B, the following lines of research have been developed within the project:

- Study of the effect of boron accumulation in a citrus crop in the medium - long term.
- Evaluation of possible phytotoxicity associated with AMD irrigation in annual crops (AMD and AMD with boron reduction).
- Identification and evaluation of early warning indicators for Boron toxicity in citrus fruits

The objectives of each of the lines and the preliminary results obtained to date.

3.2.3. Study of the effect of boron accumulation in a citrus crop in the medium - long term

To evaluate the effect of boron accumulation in a citrus orchard, an experimental plot located in Torre Pacheco, Murcia, has been selected and monitored. The plot consists of 180 grapefruit trees variety Red River grafted on Citrus Macrophyla Wester with a planting frame of 3 m between plants and 5 m between rows. The experimental design is 3 random blocks with 12 trees per treatment, each block is distributed in 3 rows of 4 trees per row (3 repetitions × 12 trees × 5 treatments = 180 trees). Measurements and sampling are being performed on the 2 interior trees at each repeat leaving the remaining 10 trees as guards to avoid edge effects. The soil is typical of the area, with a high concentration of calcium carbonate and frank texture.

Three different water resources were available:

- Campo de Cartagena Irrigation Community (CR), electrical conductivity, CE = 1.2 dS/m;
- Desalinated seawater (DB) supplied by the coastal SWRO Escombreras desalination plant (CE = 0.5 dS/m and boron concentration 0.9 ppm; and
- Farmer's water (AG) which is a mixture of CR, DB and brackish groundwater (EC = 2.0–2.5 dS/m).

Fig. 5. Image of the experimental plot of grapefruit.

These water resources are stored in 10,000 L tanks that allow additionally to make a mixture (AM) to 50% of CR and 50% of DB in a tank of 5,000 L. In addition, on-site boron reduction equipment can provide additional water with reduced boron concentration (DBS).

In this experimental plot (Fig. 5) records are being obtained of: (i) nutritional, water and physiological status of trees by foliar analysis and measurements of parameters related to the gaseous exchange, (ii) evolution of phytotoxic elements at foliar level and (iii) vegetative growth, production and quality of the harvested fruit. Tables 7–9 show the stem water potential, photosynthesis and stomatal conductance for the different treatments, respectively.

3.2.4. Evaluation of possible phytotoxicity associated with AMD irrigation in annual crops (AMD and AMD with boron reduction)

Table 7 shows the half-day water potential of the stem for the different treatments performed in the experimental plot between May 2022 and September 2022. The results show that the trees are more hydraulically stressed in the months with greater climatic demand (July–August). It is in these months that the greatest significant differences ($P < 0.05$) can be observed. A clear pattern of any effect of DB or DSB irrigation on the water status of the trees is not detected at the moment.

With respect to gas exchange (photosynthesis and stomatal conductance, respectively) for the different treatments performed in the experimental plot between May 2022 and September 2022, the results indicate that there are no significant differences between treatments and therefore irrigation with DB or DSB does not, for the moment, imply any inconvenience or advantage over the gaseous exchange parameters of the plant.

Table 7
Stem water potential for different treatments

Treatment	Stem water potential (MPa)				
	CR	DB	AM	DSB	AG
May 2022	–0.74a	–0.75a	–0.79a	–0.74a	–0.80a
July 2022	–1.36b	–1.25b	–1.52a	–1.24b	–1.26b
August 2022	–1.28c	–1.52b	–1.61ab	–1.70a	–1.08d
September 2022	–1.32ab	–1.43a	–1.46a	–1.53a	–1.13b

*Different letters indicate that there are significant differences at $P < 0.05$ between treatments each month.

3.2.5. Evolution of phytotoxic elements at foliar level

Table 8 shows the concentration of sodium and boron in leaves for the different treatments performed in the experimental plot between May 2022 and September 2022. While sodium appears not to be extremely affected by DB irrigation or leaf aging, boron increased leaf concentration as the leaf aged. The boron in citrus fruits is usually retained in the old leaves and finds difficult translocation to the young ones through phloem which explains the observed increase in time. Although it should be noted that there are no significant differences ($P < 0.05$) between treatments due to the great variability of the data, the highest values and that in some treatments such as DB and AG exceed the maximum thresholds established in literature (300 mg/kg), they met

Table 8
Sodium and boron leaf concentration for different treatments

	Sodium (mg/kg)				
	CR	DB	AM	DSB	AG
May 2022	680a	700a	520a	530a	800a
July 2022	740a	770a	740a	770a	750a
September 2022	467a	663a	839a	865a	866a
	Boron (mg/kg)				
	CR	DB	AM	DSB	AG
May 2022	54.6a	56.7a	50.6a	53.0a	53.2a
July 2022	118.2a	121.3a	125.9a	122.4a	95.8a
September 2022	199.5a	300.7a	168.9a	267.9a	317.4a

*Different letters indicate that there are significant differences at $P < 0.05$ between treatments each month.

Table 9
Development prior to the beginning of the task for the different treatments (August 2022)

August 2022	CR	DB	AM	DSB	AG
Height (m)	2.32a	2.35a	2.40a	2.57a	2.38a
Perimeter (m)	7.71a	7.92a	7.98a	8.19a	7.69a
Diameter (m)	2.45a	2.52a	2.54a	2.61a	2.45a
Canopy volume (m^3)	7.44a	8.08a	8.20a	9.38a	7.51a
Trunk section (m^2)	75.40a	75.97a	78.21a	90.65a	72.03a

*Different letters indicate that there are significant differences at $P < 0.05$ between treatments each month.

in September. It is noteworthy that the highest concentrations of boron were found in trees irrigated with DB and AG. The DSB treatment also showed a high concentration of boron in leaf, although less than 300 mg/kg; a result that could be explained by the presence of boron in the soil that is released slowly in each irrigation, accumulating in the old leaves in citrus.

3.2.6. Evolution of vegetative growth and production

Table 9 shows the vegetative development records prior to the beginning of the task (August 2022).

The results obtained for the different treatments indicate that the irrigation with DB or DSB does not, for the moment, show significant differences in vegetative growth. As for the grapefruit harvest results for the 2022 year (harvest 31 December 2022), the results did not show significant differences between the different treatments.

Regarding the quality of the fruit, no significant differences were observed between treatments for the following parameters: ° brix, acidity, maturity index, % juice, % pulp, % bark, size and color.

3.2.7. Evaluation of the possible phytotoxicity associated with AMD irrigation in annual crops (AMD and AMD with boron reduction)

To evaluate the possible phytotoxicity of DB irrigation in an annual crop, a battery of 10 polyethylene containers was installed to study the effects under controlled conditions (Fig. 6). The containers were irrigated with three different water types: (i) CR water with [B] = 0,48 ppm (3 containers), DB water with [B] = 1,29 ppm (3 containers) and AM water with [B] = 0.88 ppm (3 containers). They determined the nutritional, water and physiological status of the plants, concentration of phytotoxic elements at foliar level and vegetative development.

Table 10 shows the results of lettuce harvesting for the first 2 growing cycles; February–May 2022 and September 2022–January 2023, respectively. During the first cycle, lettuce irrigated with AM reached greater dimensions. Generally, those irrigated with DB reached lower fresh weights. During the second cycle, no significant differences ($P < 0.05$) were observed in the fresh weights between treatments. Therefore, for the moment it cannot be concluded that DB irrigation may affect the productive yield of lettuce.

Table 11 shows the boron concentration in lettuce leaves divided into root, bud and outer leaves. The results indicate that there are no significant differences in boron concentration in the different parts of a lettuce irrigated with different types of water.

3.2.8. Identification and evaluation of early warning indicators for Boron toxicity in citrus fruits

Remote sensing techniques also enable rapid, non-destructive, real-time monitoring and diagnosis of plant nutritional status. The objective of this task is to develop a specific multispectral sensor to detect changes in citrus leaves due to boron toxicity, able to differentiate these

Fig. 6. Containers for analysis of boron phytotoxicity in annual crops located in the experimental plot of the SOS AGUA XXI project.

Table 10
Measures of horizontal, vertical diagonal, height and total fresh weight of lettuce harvested in the first 2 trials

	February 2022–May 2022			September 2022–January 2023		
	CR	DB	AM	CR	DB	AM
Horizontal diagonal (cm)	15.4a	15.3a	16.9b	13.2a	15.1b	14.8b
Vertical diagonal (cm)	13.5a	13.3a	15.2b	11.8a	13.5b	13.2b
Height (cm)	15.2b	13.7a	15.5b	13.9a	15.0a	14.3a
Total fresh weight (g)	1,097b	775a	1,024b	702a	811a	769a

*Different letters indicate that there are significant differences at $P < 0.05$ between treatments each month.

changes from those caused by water stress or a nutritional deficiency. To this end, various remote sensing data sources (drones, satellites and *in-situ*) will be combined, an algorithm will be generated that will allow the early detection of boron toxicity symptoms in woody crops, specifically in citrus, which are the most affected when watered with desalinated water.

For the selection of the different early warning indicators by boron, 7 plots have been selected along the coast of Murcia irrigated during different periods with DB water with high concentration of boron (around 1 ppm). Fig. 7 shows a collage with the location of the plots and 5 orthophotos of the plots selected for boron analysis.

Table 11
Boron concentration (mg/kg) in lettuce leaves divided into root, bud and outer leaves corresponding to the first growing cycle (February–May 2022)

	CR	DB	AM
Root	23.62a	20.52a	23.02a
Bud	20.26a	17.17a	22.46a
Outer leaves	29.52a	30.70a	29.65a

*Different letters indicate that there are significant differences at $P < 0.05$ between treatments each month.

Two drone flights were conducted in July and September 2022 to obtain these indicators. Fig. 8 shows an image of the drone, the multispectral camera and the generated raster images.

4. New strategies of the Spanish government for the supply of water for agriculture in drought periods

As a recent development, on May 11, the government of Spain (MITECO) published a new Royal Decree-Law 4/2023 (https://www.boe.es/buscar/act.php?id=BOE-A-2023-11187) about new measures against drought, and whose summary is the following:

- The budget of the measures amounts to EUR 2.2 billion;
- Includes exemptions from fees and taxes for farmers affected by drought;
- The water law is amended to increase the use of

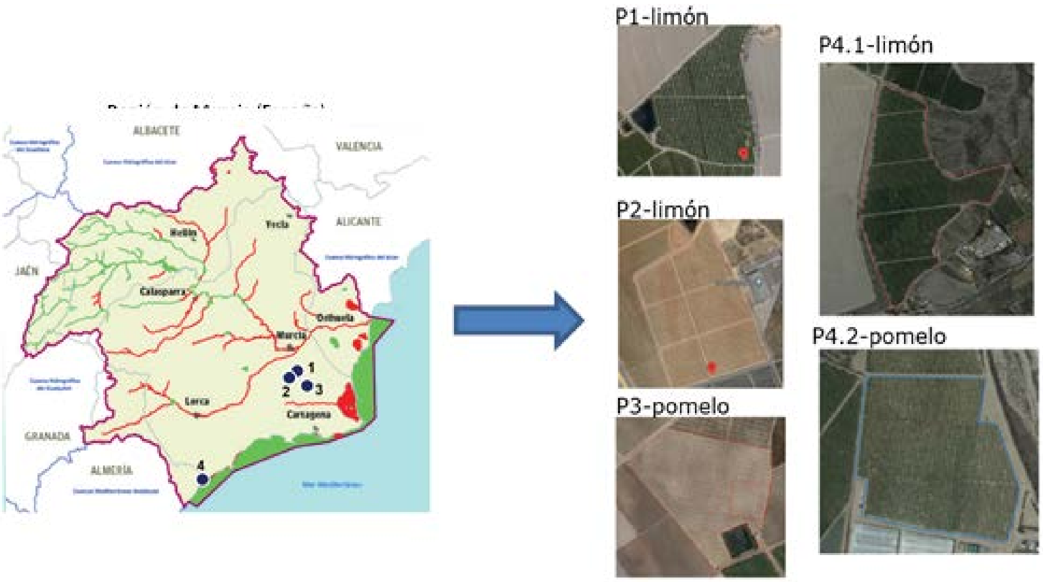

Fig. 7. Location of plots selected for the assessment of early warning indicators for boron toxicity.

Fig. 8. Procedure for multispectral imaging for the generation of boron toxicity indicators.

reclaimed water from the current 400 to 1,000 Hm^3/y by 2027;
- Includes investments in decarbonisation (photovoltaic plants) of desal plants;
- Construction of new desalination plants accelerated (Tordera II, Costa del Sol and Levante Almeriense);
- Significant investments are made in new major tertiary treatments in plants such as Rincon de León and Monte Orgegia in Alicante.

In addition, the expansions of the two largest desalination plants in Spain (and Europe), Aguilas and Torrevieja (which basically supply desal water for agriculture), whose tender will probably come out this year and the publication of a new PERTE (funding call from European Union Next Generation Funds) for digitization of the water sector for agriculture, were already approved. Similarly, some regions such as Murcia and the Valencian Community have announced additional tax reductions for desalinated water for agriculture.

5. Conclusions

Desalination and reuse of wastewater are the most effective ways to mitigate progressive water scarcity and increase resource availability for the agriculture sector.

Spain is an example of the use of desalination for agriculture with a long history in this field, demonstrating the feasibility of this application.

Desalinated water can be more expensive than water from other origins but this depends on many factors such as distance to application, energy prices, availability of other resources, etc.

All the possible technical issues (environmental, effects over soils, boron, etc.) for this application can be solved with investments which means that the key factor for the feasibility will be always water price.

Innovation is necessary to promote the use of non-conventional water resources for agriculture, and projects like LIFE DESEACROP and SOS-AGUA-XXI can help to farmers to understand the advantages of the use of high-water quality for agriculture irrigation, increasing productivity and crop quality.

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