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Environmental footprint of organic and conventional grapefruit production irrigated with desalinated seawater in Spain

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ABSTRACT

Citrus fruit production is a major food business with global relevance in the agricultural sector. The surface area of citrus irrigated with desalinated seawater in Spain, the leading citrus producer of Europe, has increased dramatically in the last decade. Desalinated seawater has alleviated water scarcity, but is facing environmental and agronomical challenges due to its high energy consumption and high boron content. The latter particularly affects citrus production due to its sensitivity to boron, since additional water treatment may be required to prevent phytotoxicity damage. The objective of this work was twofold: to quantify and compare, for the first time, the life cycle environmental footprint of (i) organic and conventional grapefruit systems irrigated with desalinated seawater, and (ii) two on-farm boron reduction technologies, namely reverse osmosis and ion exchange resins. Life Cycle Assessment has been used to evaluate the grapefruit production systems and the two technologies. The systems compared had similar characteristics (cultivar and planting density), to enable a fair comparative assessment between organic and conventional woody crops. The results show that the organic grapefruit production had better environmental performance than the conventional system in all selected impact categories and both, land and mass, functional units. The comparison of deboronation technologies showed that ion exchange resins caused a much (one order of magnitude) lower environmental footprint than reverse osmosis. Overall, this study shows that the most environmentally friendly grapefruit system irrigated with desalinated seawater was organic production combined with the use of ion exchange resins for deboronation.

1. Introduction

Citrus fruit production is an activity of global relevance in the agri-food sector, with >150 million tons of citrus fruits produced in 2021 (FAO, 2023). Spain is the leading citrus producer in Europe and the Mediterranean region, with 4.2 % of global production, followed by Egypt, Turkey, and Italy with 3.2 %, 3 %, and 2 %, respectively (Cabot et al., 2022). It is a profitable business overall, providing diversified products with high nutritional values and health benefits (Çetiner, 2022), albeit with a notable environmental footprint, higher than other agricultural systems (Martin-Gorriz et al., 2020). Over the past decades, Life Cycle Assessment (LCA) has been used to assess the environmental impacts of different citrus crops in various regions of the world. A review of LCA applied to the citrus sector was recently conducted by Cabot et al. (2022). That work highlighted that most previous studies have not considered the early life cycle phases of the cropping systems (unproductive and young trees), which should be included for a more comprehensive assessment. It also showed that the most studied citrus fruit production systems with LCA were orange, lemon and mandarin (e.g., Bell and Horvath, 2020; Machin Ferrero et al., 2022 and; Martin-Gorriz et al., 2020, respectively) and that grapefruit production systems as still being underrepresented.

Moving from intensive conventional cropping systems to more eco-friendly organic production models has shown potential to reduce the

Abbreviations: BRT, Boron Reduction Technology; CF, Carbon Footprint; CGIX, Conventional Grapefruit production with Ion Exchange resins; CGRO, Conventional Grapefruit production with Reverse Osmosis; DSW, Desalinated Seawater; FU, Functional Unit; FWEC, Freshwater Ecotoxicity; FWEU, Freshwater Eutrophication; IX, Ion Exchange resins; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; OFT, Ozone Formation, Terrestrial ecosystems; OGIX, Organic Grapefruit production with Ion Exchange resins; OGRO, Organic Grapefruit production with Reverse Osmosis; PPPs, Plant Protection Products; RO, Reverse Osmosis; SOD, Stratospheric Ozone Depletion; TA, Terrestrial Acidification.

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environmental footprint for many woody crops (e.g., Ribal et al., 2017; Ben Abdallah et al., 2021 and; Bonales-Revuelta et al., 2022). However, organic systems do not always outperform conventional ones from an LCA perspective, particularly when footprint analyses are based on mass production rather than land units, due to the generally lower productivity of organic farming. In fact, many LCA studies have reported results for systems with different agronomic characteristics, often with much higher productivity in conventional systems due to a higher planting density and/or the use of more productive cultivars (e.g., Pergola et al., 2013; Ribal et al., 2017; Ben Abdallah et al., 2022). Apart from productivity differences, several gaps have been identified in the LCA of organic systems, notably the lack of representative manufacturing inventories of organic plant protection products (PPPs) and organic fertilizers (Montemayor et al., 2022).

An added layer of complexity to greener fruit production is the integration of non-conventional water resources to cope with the current global water scarcity crisis, which is expected to worsen (Qadir et al., 2007; Amali et al., 2020). The adoption of desalinated seawater (DSW) for irrigation is considered a viable option to alleviate water scarcity in dry coastal regions (Barron et al., 2015; Suwaileh et al., 2020). However, DSW has chemical singularities and requires a high energy consumption for its production and allocation, which may jeopardize crop productivity and profitability (Martínez-Alvarez et al., 2023). Globally, the daily production of DSW exceeds 100 million m^3, with almost two thirds of that being produced by reverse osmosis (RO) (Jones et al., 2019). If only one RO stage is performed, the DSW produced usually has a relatively high boron concentration (Najid et al., 2021), which may pose a phytotoxicity hazard. In particular, boron concentrations of over 0.5 mg L^{-1} have been reported to cause toxic effects to some sensitive crops such as citrus trees (Vera et al., 2023). In Spain, a concentration of 1.5 mg L^{-1} is allowed for both human consumption and irrigation water, and 2.4 mg L^{-1} when the origin of the water is DSW (Royal Decree 3/2023). Therefore, citrus farmers need to mix DSW with other resources, if available, or use on-farm boron reduction systems to prevent toxicity damage (Imbernón-Mulero et al., 2022a). The technical and economic aspects of on-farm boron reduction have been recently studied, in particular with RO (Imbernón-Mulero et al., 2022a) and ion exchange resins (IX) (Imbernón-Mulero et al., 2022b). However, the environmental impact of such systems used for citrus production has yet to be covered in the scientific literature, to our knowledge.

The main objective of this study is to calculate and compare the environmental footprint of organic and conventional grapefruit production systems irrigated with DSW in southeastern Spain. To our knowledge, this is the first LCA study that quantifies the environmental impacts per unit of cultivated land and total mass produced for these systems. A specific and novel objective of the study is the application of the LCA methodology to quantify the environmental impacts of RO and IX for the on-farm deboronation of DSW. Furthermore, this study also addresses gaps identified in the LCA of citrus, such as the consideration of all the crop stages (from planting to the full production phase) and the inclusion of data inventories for the manufacture of PPPs specific to organic production. According to Montemayor et al. (2022), previous LCA studies have used alternative PPP inventories that are not representative of organic management. The stages and phases with the highest impacts were identified, in order to provide insights for policy design to improve the environmental sustainability of DSW use in citriculture, focusing on the impacts of on-farm boron reduction.

2. Material and methods

2.1. Case study

Two grapefruit systems (cultivar “Star Ruby”), organic and conventional, irrigated with DSW, located in the Region of Murcia (southeastern Spain) have been studied. The region has a semi-arid climate with hot dry summers, mild winters, and abundant but sporadic rainfall in autumn (CHS, 2018). The agricultural production area covers about half of the region's land area (11,313 km^2, ESYRCE, 2018). The irrigated agricultural area represents 47 % of the agricultural fields (CARM, 2022). A significant amount (around 200 Mm^3 $year^{-1}$) of the water for agricultural irrigation is provided by desalination of seawater (Martínez-Alvarez et al., 2023). Within an area of 47,000 ha dedicated to woody crops irrigated with DSW, citrus trees are the most common crop (74.7 %, Imbernón-Mulero et al., 2022a). The Region of Murcia is the third largest producer of citrus fruits in Spain, with 14 % of national production in 2021 (MAPA, 2022), and was the leader in grapefruit cultivation with 42 % of the total production in 2021 (MAPA, 2022). Around 20 % of this crop is certified as organic production in Spain and the study area accounts for 23 % of the country's organic grapefruit area (MAPA, 2022).

The two Boron Reduction Technologies (BRT) included in this study (RO and IX) were trialed in 2021 at a grapefruit farm located in Torre Pacheco, Murcia, Spain (37°47′30” N, 1°03′85” W; 30 m above sea level). The technical and economic assessment results of the BRTs with an experimental flow rate of 1m^3 h^{-1} and scaled to an average flow rate of 21 m^3 h^{-1} (147,000 m^3 $year^{-1}$) were presented for RO in Imbernón-Mulero et al. (2022a) and for IX in Imbernón-Mulero et al. (2022b). The physical and chemical properties of the raw and treated DSW with both technologies were also detailed in those studies.

2.2. Life Cycle Assessment

The environmental assessment was carried out in accordance with the specific ISO standards for LCA guidelines and requirements (ISO 14040, 2006; ISO 14044, 2006). Therefore, the four main LCA stages defined by ISO 14040 have been included: (i) goal and scope definition; (ii) life cycle inventory (LCI) analysis; (iii) life cycle impact assessment and; (iv) interpreting the results.

2.2.1. Goal and scope definition

The goal of the study was to quantify the environmental impacts of organic and conventional grapefruit production using DSW for irrigation with on-farm deboronation in southeastern Spain. In addition, another specific objective of the study was to compare the environmental performance of two on-farm BRTs, RO and IX. The scope of the LCA study was grapefruit production from ‘cradle-to-farm-gate’, taking into account all materials and energy flows from raw material extraction through to grapefruit harvesting at the farm gate.

The two grapefruit systems (organic and conventional) had the same planting density (416 trees ha^{-1}) and used the same cultivar “Star Ruby”. Table 1 shows the main characteristics of the studied cropping

Table 1
Main characteristics of the grapefruit systems studied.

Characteristic	Organic system	Conventional system
Cultivation method	Organic	Conventional
Cultivar	Star Ruby	Star Ruby
Planting density (trees ha^{-1})	416	416
Tree spacing	6 × 4	6 × 4
Water for irrigation	Desalinated seawater	Desalinated seawater
Fertilization	Fertigation	Fertigation
Weed control	Mechanical	Chemical and mechanical
Harvesting	Manual	Manual
Pruning and pruning residues	Manual and mechanical	Manual and mechanical
Disease Control	Bio protection products	Conventional pesticides
Lifespan (years)	25	25
Unproductive juvenile (years)	2	2
Young (years)	3	3
Full production (years)	20	20
Life cycle production (t ha^{-1}/25 year)	1460	1625

systems. These systems, combined with the two BRTs, yielded the four scenarios evaluated: Organic Grapefruit production (i) with RO (OGRO) and (ii) with IX (OGIX); and Conventional Grapefruit production system (iii) with RO (CGRO) and (iv) with IX (CGIX). The scenarios were evaluated over the entire life cycle of the grapefruit crop (25 years), divided into four phases: planting, unproductive juvenile, young, and full production (Table 1). The functional units selected were 1 ha of cultivated grapefruit area and 1 t of grapefruit, following the recommendations of van der Werf et al. (2020) for comparative evaluations of organic vs. conventional production systems.

For the boron reduction stage, either with RO or IX, the scope was the production of deboronated DSW at the farm. The functional unit (FU) selected was 1 m^3 of deboronated DSW for irrigation. A lifespan of 15 years was considered for the equipment of both technologies, in accordance with the manufacturers' specifications. Table 2 shows the main elements of the two BRTs. A detailed description of the structural elements and operating conditions can be found for RO in Imbernón-Mulero et al. (2022a) and for IX in Imbernón-Mulero et al. (2022b).

All the processes of the grapefruit production chain from the extraction of raw materials to the farm gate are within the system boundaries in the background and foreground systems. Fig. 1 shows the system boundaries and the flows included in the analysis. Fig. 2 shows the detailed flow chart of the production and distribution of DSW and the on-farm boron reduction. The cropping phases of each scenario were structured into the following stages (or processes):

- On-farm boron reduction:
  This stage included the following components associated with the implementation, operation and end of use of the BRTs: (i) all materials used for the infrastructure, such as steel, plastic, resins and zeolite, as well as their manufacturing, transport, and waste management. Both technologies had the same structure except for the following elements: the ionic exchange filter and resins in the IX technology, and specific tubing, membranes and system of sweeping and cleaning in the RO technology (Table 2); (ii) the energy consumed in the boron-reduction process; (iii) the chemical reagents; (iv) the raw water consumed; and (v) the rejected water (brine) for the RO technology, with the corresponding emissions. The rejection flow of the IX technology was not considered, since it was observed to be insignificant (0.4 % of the raw water, Imbernón-Mulero et al., 2022b).
- Irrigation:
  The on-farm irrigation system covered the following: (i) materials, transport, and manufacturing of equipment (irrigation heads, solenoid valves, tanks, schedulers, filters, polyethylene, and polyvinylchloride pipes), with their associated emissions; (ii) the reservoir and the deployment of the shed for the irrigation head; (iii) water and energy consumed for irrigation and associated emissions (fuel consumption and production and transmission of electricity, including grid leakage). The amount of electricity consumed for irrigation included seawater pumping, RO desalination, and network distribution (Fig. 2). It should be noted that electricity consumption has been reported to be the main impact source of RO desalination (Du, 2019; Najid et al., 2021; Fayyaz et al., 2023). The chemicals and infrastructure used for DSW production were not included within the system boundaries.
- Fertilizers:
  This stage included the production of nitrogen (N), phosphate (P_2O_5) and potassium (K_2O) fertilizers required for each cropping phase, and their packaging and transport to the field, with their associated emissions. The following emissions were accounted for in the field application of fertilizers: (i) emissions to air of nitrous oxides (N_2O), ammonia (NH_3) and nitrogen oxides (NO_x) and emissions to water of nitrates (NO_3^-) for N-fertilizers and (ii) emissions to water of phosphates (PO_4^{3-}) for P_2O_5 fertilizers. In both grapefruit systems (organic and conventional) the fertilizers were applied by fertigation.
- Plant Protection Products:
  This stage consisted in the manufacture and synthesis of the chemical and organic components of the PPPs used, their transport to the farm and the disposal of waste at the end of their use. The specific manufacturing of the PPPs used in the organic system was accounted for following the recommendations of Montemayor et al., 2022. The PPPs used in the organic system were: spinosad, *bacillus thuringiensis*, orange oil, azadirachtin, potassium soap and paraffin oil. In the case of the conventional system, the total amount of active ingredients of the conventional pesticides used was accounted for.
- Machinery:
  This stage covers the manufacture, transport, use, repair, and maintenance of the agricultural machinery needed for field agricultural practices (soil management, pesticide and herbicide application and treatment of pruning residues), as well as the corresponding fuel consumption and associated air emissions. The following farm machinery was used in the grapefruit systems studied: tractors, boom sprayers (herbicide application in the conventional system), soil management equipment, air sprayers (PPP application), transport trailers and chippers (pruning).

A distance of 50 km was considered for the transport of fertilizers, PPPs, chemicals and infrastructure materials.

2.2.2. *Life cycle inventory*

This section describes the specific data used to create the LCI. Most data used for the LCI, particularly for the foreground processes, correspond to primary data collected from farmers and experimental plots, and field surveys and trials previously conducted and published by the authors. Data from the literature and the ecoinvent v.3.9.1 database (ecoinvent, 2022) were also used, especially for the background processes. The specific data sources used for each stage are summarized in Table S1 (Supplementary Data). The data used for all stages are detailed below. For more clarity, a separate section has been devoted to the boron-reduction stage.

2.2.2.1. Irrigation, fertilizers, plant protection products and machinery stages of grapefruit production. Table 3 shows the values of the main inputs and outputs in the life cycle phases of the organic and conventional grapefruit production systems, without the boron-reduction stage. The LCI primary (foreground) and secondary (background) data for grapefruit production were the following:

(i) Foreground data:

- Productivity, field farming practices and machinery use were gathered directly from two farms located in the Region of Murcia (Spain), which had trees in the phase of full production (planted in 2004 for

Table 2
Main elements of the on-farm boron reduction technologies.

Common elements	
Feed pump	
Pre-treatment system	
Activated carbon microfilter	
Microfilter	
pH meter	
Electrical conductivity meter	
Dosing pump	
Specific elements	
Reverse Osmosis	Ion Exchange Resins
RO units	IX column
Sweeping and cleaning system	Resins

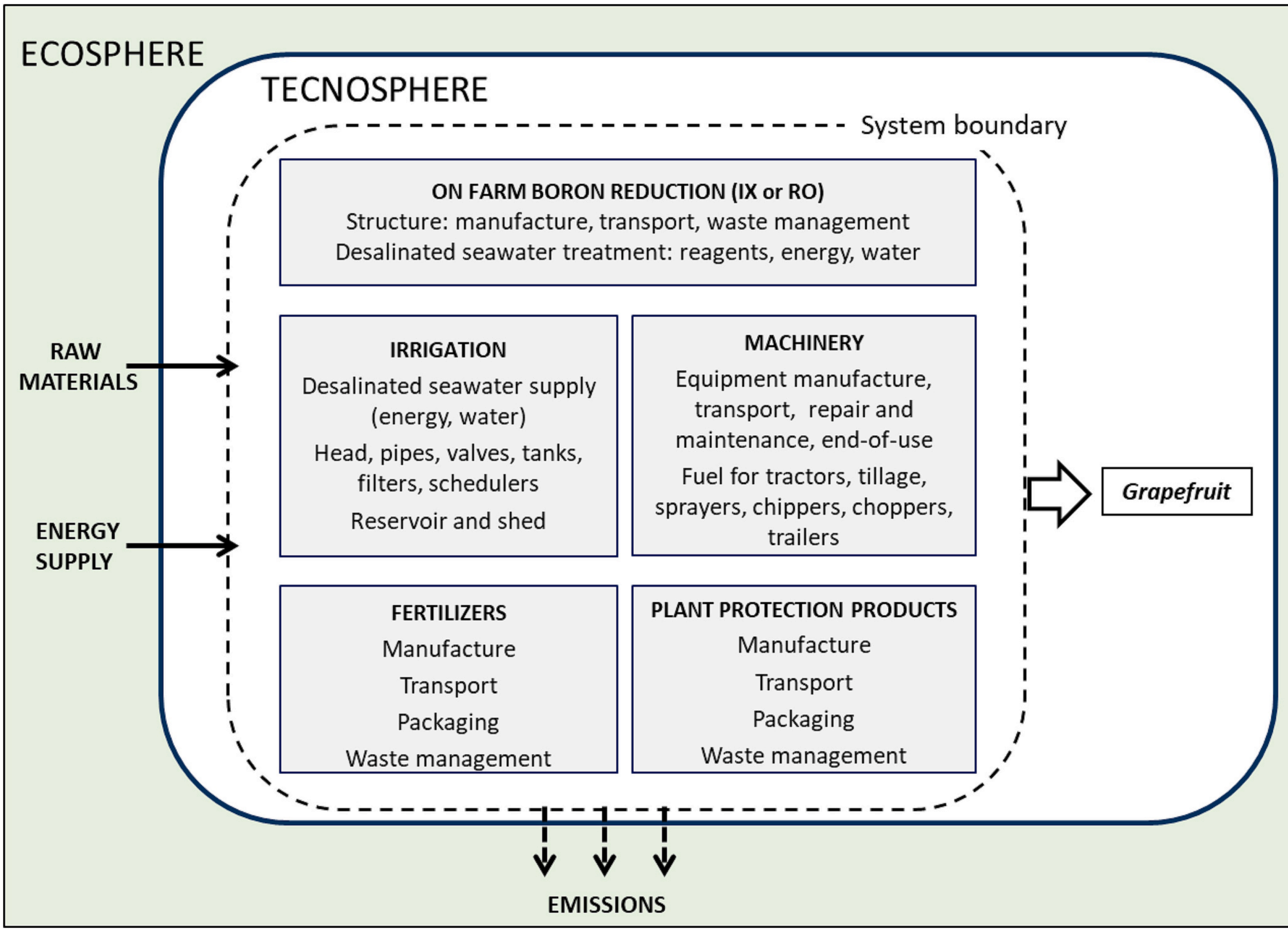

Fig. 1. Flow diagram of cradle-to-farm-gate grapefruit production with on-farm deboronation of desalinated water.

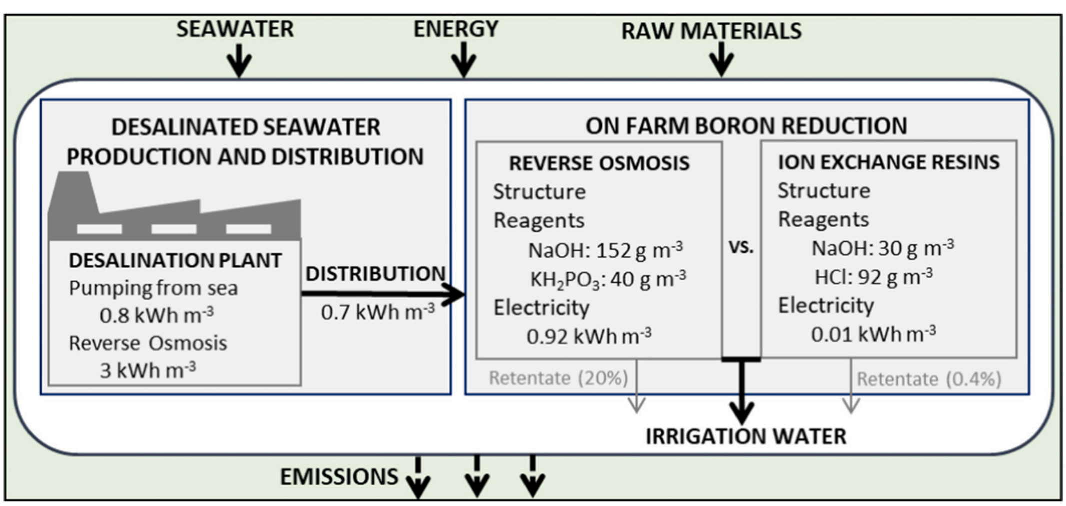

Fig. 2. Flow diagram of the production and distribution of DSW and the on-farm boron reduction.

the conventional system, and in 2013 for the organic system). The data collected included: (i) irrigation water and corresponding energy consumption at farm level; (ii) type and amounts of fertilizers and PPPs; (iii) type and time of use of machinery for field operations and the associated fuel consumption. These data were complemented with data from the literature (Table S1, Supplementary Data), such as statistics and estimates provided by García García (2014, 2018) and technical recommendations by Audsley et al. (1997) and Márquez (2004), relating to grapefruit field management in the study area.

- The energy consumed for the DSW supply, which included seawater intake pumping, the desalination process and network distribution as indicated in a previous study (Martínez-Alvarez et al., 2019).

Table 3
Main inputs and outputs for the processes included in the life cycle phases of the organic and conventional grapefruit production systems (without on-farm boron reduction).

Input/output	Units	Organic				Conventional			
		Planting	Juvenile	Young	Full production	Planting	Juvenile	Young	Full production
Irrigation									
Water	$m^3\ ha^{-1}$	–	1249	6817	109,074	–	3003	9586	118,400
Electricity	$kWh\ ha^{-1}$	–	5620	30,678	490,833	–	13,514	43,137	532,800
Irrigation system[a]									
Irrigation head	$kg\ ha^{-1}\ year^{-1}$	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
PE pipeline and emitters	$kg\ ha^{-1}\ year^{-1}$	227	227	227	227	227	227	227	227
PVC pipeline	$kg\ ha^{-1}\ year^{-1}$	68	68	68	68	68	68	68	68
HPDE film (reservoir)	$kg\ ha^{-1}\ year^{-1}$	36	36	36	36	36	36	36	36
Fertilizers doses Fertilizers doses									
N	$kg\ ha^{-1}$	–	52	185	2009	–	134	357	3490
P_2O_5	$kg\ ha^{-1}$	–	24	99	1068	–	63	162	1555
K_2O	$kg\ ha^{-1}$	–	35	169	1989	–	97	261	2557
Emissions to air									
NH_3	$kg\ ha^{-1}$	–	1.5	5.6	60.3	–	4	11	105
N_2O	$kg\ ha^{-1}$	–	0.6	2.3	25.1	–	2	4	44
NO_x	$kg\ ha^{-1}$	–	0.1	0.2	2.5	–	0.2	0.4	4
Emissions to water									
NO^{3-}	$kg\ ha^{-1}$	–	2.6	9.3	100.4	–	7	18	174.5
PO_4^{3-}	$kg\ ha^{-1}$	–	1.2	4.9	53.4	–	3	8	77.8
Plant protection products									
Paraffin oil	$kg\ ha^{-1}$	–	–	37.35	560.3	–	–	–	–
Azadirachtin	$kg\ ha^{-1}$	–	–	0.04	0.1	–	–	–	–
Potassium soap	$kg\ ha^{-1}$	–	–	–	22.8	–	–	–	–
Orange oil	$kg\ ha^{-1}$	–	–	–	4.5	–	–	–	–
Bacillus thuringiensis	$kg\ ha^{-1}$	–	–	–	2.7	–	–	–	–
Spinosad	$kg\ ha^{-1}$	–	–	–	0.4	–	–	–	–
Total	$kg\ ha^{-1}$	–	–	37.39	590.8	–	10	36	388
Machinery	$kg\ ha^{-1}$								
Time	$h\ ha^{-1}$	304	–	15.3	175.3	304	11	39	373
Diesel for reservoir excavation	$kg\ ha^{-1}$	5640	–	–	–	5640	–	–	–
Diesel for field operations	$kg\ ha^{-1}$	455	–	92	1081	455	26	125	1256

[a] Average for the life cycle (25 years).

- The components and materials used for the establishment of the irrigation system for a cultivated area of 1 ha of citrus farm and their corresponding lifespan were those indicated for woody crops in the study area in a previous study (Martin-Gorriz et al., 2020).
- Air emissions from fertilizer application to the field (N_2O, NH_3 and NO_x) were calculated as per Audsley et al. (1997) and Brentrup et al. (2000). Nitrate (NO_3^-) leaching to groundwater was calculated using the estimation model of Martínez-Alcantara et al. (2012). The SALCA-P model (Nemecek and Kagi, 2007) was used to calculate the emissions of phosphorus (PO_4^{3-}) to surface water and ground water. The amounts of these emissions for the LCI of the two systems are shown in Table 3. Emissions from diesel consumption were retrieved from the ecoinvent database (ecoinvent, 2022).

(ii) Background data:

- The ecoinvent v.3.9.1 database (ecoinvent, 2022) was used for: (i) manufacturing processes of fertilizers, conventional pesticides, agricultural machinery, irrigation system materials, and their associated emissions; (ii) energy production (fuel and electricity) and; (iii) transport and waste disposal. The use of the ecoinvent database is recommended in comparative studies of organic vs. conventional farming systems (Montemayor et al., 2022).
- Data for the manufacture of PPPs used in the organic system were collected from the literature, following the recommendations of Montemayor et al. (2022), in order to carry out a more representative comparative assessment. The following sources were used: (i) the bioprocess modeler CeBER "Centre for Bioprocess Engineering Research" (Harding and Harrison, 2016a, 2016b) for Spinosad and *bacillus thuringiensis*; (ii) Kumar et al. (2021) for the production of 1 kg of neem oil as a representative proxy for azadirachtin; (iii) Beccali et al. (2009) for the manufacture of orange oil and; (iv) Montemayor et al. (2022) for potassium soap. For paraffin oil, data were retrieved from the ecoinvent database.

2.2.2.2. Boron-reduction stage. The data for the LCI of both BRTs was compiled from experimental trials, the manufacturer, and the literature (Table S1). The data collected for this study includes all the infrastructure materials, chemical reagents, energy consumption, water and air emissions and waste generated by BRTs with a production capacity of 21 $m^3\ h^{-1}$ of deboronated DSW (147,000 $m^3\ year^{-1}$). The inflows, outflows and electricity consumption of the BRTs are shown in Fig. 2 and Table S2. The water production rate of IX was nearly 100 % while it was 80 % for RO. The latter was the maximum rate recommended by the provider to avoid frequent salt saturation of the membranes of the on-farm (small-scale) system. The ecoinvent database was used for the background data: manufacturing and transport of materials and chemicals, electricity generation mix, and waste transport and disposal. The chemical properties of the rejected water (emissions to water) were measured in the laboratory.

The materials and processes accounted for in the LCI of the BRTs structure are summarized in Table 4. For all raw materials, processes related to manufacturing, such as plastics extrusion and blow molding and steel metal working, were included. The extraction and transport of materials and waste management were also considered. The type and amount of chemicals used for deboronation as well as the lab chemical characterization of the rejected water by the RO system are given in Table S3.

2.2.3. Life Cycle Impact Assessment

The quantification of environmental impacts and the identification of hotspots were carried out using the life cycle impact assessment (LCIA) methodology with the openLCA v.1.11.0 software. The ReCiPe midpoint (H) method (Huijbregts et al., 2017) was used to perform the LCIA. Midpoint indicators are recommended for representing impacts derived from agricultural production, since for communicating results they are readily understood, and because a limited number of indicators can effectively summarize relevant information (Hersener et al., 2011; Tendall and Gaillard, 2015). Six midpoint impact categories were selected for the environmental assessment: carbon footprint (CF, kg CO_2 eq); freshwater ecotoxicity (FWEC, kg 1,4-DCB); freshwater eutrophication (FWEU, kg P eq); terrestrial acidification (TA, kg SO_2 eq); stratospheric ozone depletion (SOD, kg CFC-11 eq); and ozone formation, terrestrial ecosystems (OFT, kg NO_x eq). These categories have previously been used for the environmental sustainability assessment of both citrus crop systems and water treatment technologies (e.g., Cabot et al., 2023; Alguacil-Duarte et al., 2022; Fayyaz et al., 2023). These impacts have been chosen in accordance with the product category rules for water supply included in the international environmental product declaration systems (Environdec, 2022; Alguacil-Duarte et al., 2022). Other topics should be considered in a broader context, but here we focus on impacts relevant to energy, agricultural, and industrial processes (Ben Abdallah et al., 2021; Alguacil-Duarte et al., 2022), in order to simplify the model to the level of accuracy needed for problem solving and decision support, as recommended for the multifunctionality assessment context (Zander et al., 2008).

Table 4
Materials and processes accounted for in the Life Cycle Inventory of the structure of the boron reduction technologies reverse osmosis and ion exchange resins.

Material	Component	Unit	RO	IX
Carbon steel	Main structure and frame	kg	690	690
Stainless steel	Clamps and pressurizers	kg	306.4	258.2
PVC	Pipes	kg	220	220
PP	Pipes	kg	150	150
PE	Tanks	kg	781	706
PA	Filters and membranes	kg	596	296
GFRP	Pipes	kg	295.2	242
Zeolite	Filter load	kg	1020	1020
Resins	Resins	kg	_	1487.5

Material	Process	Unit	RO	IX
Steel	Manufacturing, metal working	kg	996.4	948.2
PVC, PP	Extrusion, plastic pipes	kg	370	370
PE	Blow molding, tanks	kg	781	706
Material transport to production sites	Freight, lorry 7.5–16 metric ton	tkm	202.9	253.5

Material	Waste	Unit	RO	IX
Carbon steel	Recycling center	kg	690	690
Stainless steel	Recycling center	kg	306.4	258.2
PVC	Recycling center	kg	220	220
PP	Recycling center	kg	150	150
PE	Recycling center	kg	781	706
PA	Recycling center	kg	596	296
GFRP	Landfill	kg	295.2	242
Zeolite	Landfill	kg	1020	1020
Resins	Landfill	kg	_	1487.5
Waste transport to recycling center	Freight, lorry 7.5–16 metric ton	tkm	137.2	116.0
Waste transport to landfill	Freight, lorry 7.5–16 metric ton	tkm	65.8	137.5

PVC: polyvinylchloride; PP: polypropylene; PE: polyethylene; PA: polyamide; GFRP: glass fiber reinforced polyester; tkm: tonne-kilometer.

3. Results

3.1. Environmental impacts of the evaluated scenarios

Table 5 shows the impact indicator values for the organic (O) and conventional (C) grapefruit (G) production systems with the two deboronation technologies (RO and IX) and the impact variation between the two systems for each deboronation technology (i.e., OGRO vs. CGRO and OGIX vs. CGIX, expressed as the percentage difference of impact of organic vs. conventional).

For all the evaluated impact categories, the organic systems (OGRO and OGIX) had lower environmental footprints than the corresponding conventional systems (CGRO and CGIX) for both land and mass FUs. The impact reduction derived from growing organic rather than conventional grapefruit ha^{-1} FU ranged from 10.3 % for OFT to 38.2 % for SOD (with an average reduction of 18.4 % for all categories together). The higher environmental impacts of conventional systems were related to the higher consumption per ha of inputs such as water, electricity, and fertilizers, as well as the use of synthetic PPPs (Table 3).

Table 5
Environmental impacts a) per ha FU; b) per t FU of the evaluated scenarios: Organic Grapefruit production system with RO (OGRO) and with IX (OGIX) and Conventional Grapefruit production system with RO (CGRO) and with IX (CGIX). The variation (Δ) is calculated as [(impact of organic / impact of conventional) − 1] * 100.

Impacts	Unit	OGRO	CGRO	Δ(%)	OGIX	CGIX	Δ(%)
a) per ha FU							
CF	kg CO_2 eq	3.45×10^5	4.05×10^5	−14.8	2.85×10^5	3.38×10^5	−15.7
FWEC	kg 1,4-DCB	2.52×10^4	2.87×10^4	−12.2	2.02×10^4	2.31×10^4	−12.6
FWEU	kg P eq	3.62×10^2	4.32×10^2	−16.2	1.68×10^2	2.15×10^2	−21.9
TA	kg SO_2 eq	2.14×10^3	2.54×10^3	−15.7	1.76×10^3	2.12×10^3	−17.0
SOD	kg CFC11 eq	1.19	1.86	−36.0	1.07	1.73	−38.2
OFT	kg NO_x eq	1.31×10^3	1.46×10^3	−10.3	1.12×10^3	1.25×10^3	−10.4
b) per t FU							
CF	kg CO_2 eq	2.36×10^2	2.49×10^2	−5.2	1.95×10^2	2.08×10^2	−6.3
FWEC	kg 1,4-DCB	1.73×10^1	1.77×10^1	−2.3	1.39×10^1	1.42×10^1	−2.1
FWEU	kg P eq	2.48×10^{-1}	2.66×10^{-1}	−6.8	1.15×10^{-1}	1.32×10^{-1}	−12.9
TA	kg SO_2 eq	1.47	1.57	−6.4	1.21	1.30	−6.9
SOD	kg CFC11 eq	8.17×10^{-4}	1.14×10^{-3}	−28.3	7.36×10^{-4}	1.06×10^{-3}	−30.6
OFT	kg NO_x eq	8.97×10^{-1}	8.99×10^{-1}	−0.2	7.65×10^{-1}	7.67×10^{-1}	−0.3

Results per t FU also showed the lower environmental footprint of the organic system, although the differences between them were substantially smaller. In this case, the impact reduction ranged from 0.2 % for OFT to 30.6 % for SOD, with an average reduction of 9 % for all categories together. This is due to environmental impacts per t being directly related to productivity, which was 10 % lower in the organic system (Table 1), despite having the same cultivar and planting density as the conventional system.

Within each cropping system (organic or conventional), those systems using IX technology (CGIX and OGIX) showed far better environmental performance than those with RO for boron reduction (CGRO and OGRO) in all the impact categories and for both FUs. The detailed difference in impacts between the technologies is shown in the following section, but overall, the lesser impact of IX was mainly due to the lower consumption of electricity and chemical reagents in the boron reduction process. In fact, introducing the IX technology into the grapefruit production systems caused only minor variations in impacts, with a maximum increase of 6 % in FWEC and up to 2 % in TA, SOD, and OFT. On the contrary, the use of RO technology increased the impacts on grapefruit production by up to 123 % in FWEU, 32 % in FWEC, and 25 % in CF.

Fig. 3 shows the contribution of each LCA stage to each impact category for all the scenarios in the full production phase. The stages with the highest contributions in all the impact categories were irrigation and fertilizers, and boron reduction for the case of systems with RO. The main contributor to most categories was the irrigation stage, accounting for up to 86 % for FWEC and 79 % for OFT in OGIX. This was mainly due to the high electricity consumption for the production and distribution of DSW (about 4.5 kWh m^{-3}). The RO for boron reduction had high impacts in the respective systems (CGRO and OGRO) with the highest contribution to the FWEU impact category (up to of 56 % in the OGRO system), again mainly caused by the elevated electricity requirements of RO. The fertilizers stage dominated the SOD impact category in all the scenarios, since it was the main source of N_2O emissions to the air, with a maximum contribution of 85 % in CGIX. PPPs and farm machinery had the lowest contributions in all systems. In particular, PPPs had the lowest impacts in the organic systems, due to the low impacts of manufacturing the organic crop protection product (with a minimum contribution of 0.18 % to FWEU in OGRO, and a maximum contribution of 1.12 % to SOD in OGIX).

3.2. Impacts of boron reduction technologies

Table 6 shows the environmental impacts of RO vs. IX for the production of 1m^3 of deboronated DSW. The IX had a much lower (at least one order of magnitude less) environmental footprint than RO in all categories. The impact was from 41 to 5 times lower for FWEU and FWEC, respectively. These differences are mainly due to RO needing much higher quantities of inputs (particularly electricity) for the DSW treatment. In fact, RO consumed 0.91 kWh m^{-3} more than IX and, additionally, it had a lower water production rate compared to IX (80 % in RO vs. 99.6 % in IX, Table S2).

The boron-reduction stage was divided into two substages, DSW treatment and structure, to further analyze the differences in footprint between the BRTs. The substage contributing most to the impacts was the DSW treatment for both technologies and all categories except for SOD in IX, since resins used in the structure are a major N_2O source (Table 7). Fig. 4 shows that the footprint of RO in the dominant substage, the DSW treatment, was >80 % of the footprint of IX in all the categories. On the contrary, the impact of both BRTs for the structure substage was roughly equivalent in all the categories, except for SOD, as highlighted above. The latter equivalence was to be expected since most of the components and materials (type and amount) used for the infrastructure of the two technologies were similar (Tables 2 and 4), with the main difference being the use of membranes for RO and resins for IX.

Looking at the processes of the DSW treatment substage, most of the impact (>70 %) in all the categories except SOD were due to the electricity consumption in RO, and due to the use of chemicals (>77 %) in IX (Table 7). Specifically, most air emissions, such as CO_2 (CF), SO_2 (TA) and NO_x (OFT), were dominated by the electricity used in RO and the chemicals in IX. This aspect was also observed for the key emissions to groundwater, such as copper and phosphate, related to the FWEC and

Table 6
Main impacts of the on-farm production of deboronated DSW for irrigation per m^3 FU with the boron reduction technologies reverse osmosis and ion exchange resins.

Impacts per m^3	Unit	RO	IX	RO/IX
CF	kg CO_2 eq	5.83×10^{-1}	6.61×10^{-2}	9
FWEC	kg 1,4-DCB	5.25×10^{-2}	9.77×10^{-3}	5
FWEU	kg P eq	1.70×10^{-3}	4.17×10^{-5}	41
TA	kg SO_2 eq	3.55×10^{-3}	3.03×10^{-4}	12
SOD	kg CFC11 eq	1.22×10^{-6}	2.04×10^{-7}	6
OFT	kg NO_x eq	1.81×10^{-3}	1.71×10^{-4}	11

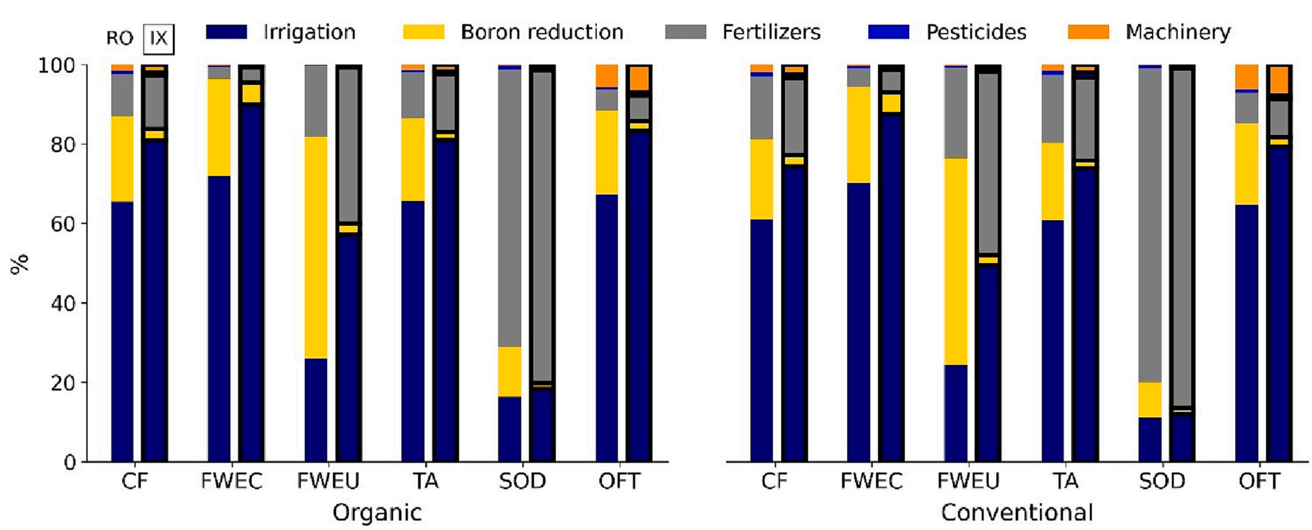

Fig. 3. Contribution of the processes to the selected impact categories in the full production phase of (a) Organic and (b) Conventional grapefruit production system, with RO and with IX. For each impact category, the left bar refers to RO and the right bar (edge in black) to IX.

Table 7
Elementary flow (EF), compartment, main substage, and main process for the reverse osmosis and ion exchange resins boron reduction technologies for each impact category (IC).

IC	EF	Compartment	Main substage	Main process RO	Main process IX
CF	CO_2	Air	DSW treatment	Electricity (71.12 %)	Chemicals (77.5 %)
FWEC	Cu	Groundwater	DSW treatment	Electricity (71.34 %)	Chemicals (81.03 %)
FWEU	PO_4^{3-}	Groundwater	DSW treatment	Electricity (73.00 %)	Chemicals (87.56 %)
TA	SO_2	Air	DSW treatment	Electricity (76.44 %)	Chemicals (81.78 %)
SOD	N_2O	Air	DSW treatment	Chemicals (81.03 %)	
SOD	N_2O	Air	Structure		Resins (81.03 %)
OFT	NO_x	Air	DSW treatment	Electricity (77.09 %)	Chemicals (80.44 %)

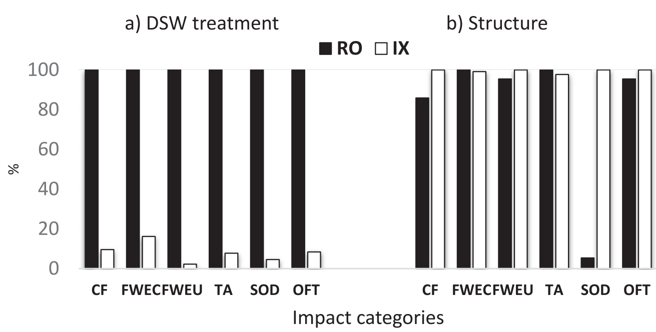

Fig. 4. Impact comparison per m^3 of deboronated water produced with reverse osmosis vs. ion exchange resins for the life cycle stages: (a) Water treatment and (b) Structure. The maximum value is set at 100 % for each impact category.

FWEU impact categories, respectively. However, N_2O emissions to air, related to the SOD impact category, were mainly influenced by the application of chemicals in the RO treatment, and the high amounts of resins used in the structure of IX. In the IX technology, the production and application of hydrochloric acid contributed the most to the chemical impacts, with a contribution of up to 78 % in FWEU.

4. Discussion

The organic grapefruit system showed better environmental performance than the conventional system in all the impact categories and in both land and mass FUs. The outperformance of the organic system was less apparent for mass FU (i.e., impacts per t), as the yield was 10 % lower than with the conventional system, despite using the same cultivar and planting density. Our results are in line with previous studies comparing organic and conventional citrus crops per ha, such as Pergola et al. (2013) for lemon and orange in Italy, Ribal et al. (2017) for orange production in Spain and Nicolo et al., 2018 for clementine in Spain and Italy. Regarding results per mass FU, Bonales-Revuelta et al. (2022) reported that organic orange production in Mexico outperformed conventional production in most impact categories. However, Ribal et al. (2017) found no differences for some impact categories, due to the high production variability of the studied systems. For other cropping systems, numerous studies have revealed lower impacts of the conventional system per mass FU (e.g., Foteinis and Chatzisymeon, 2016; Ben Abdallah et al., 2022; Coppola et al., 2022). In our case study, the difference in production between the two systems was not significant enough to invert the results per t FU.

The use of LCA to compare the environmental performance of organic vs. conventional farming systems remains a controversial topic and a matter of scientific discussion and debate (Meier et al., 2015; van der Werf et al., 2020; Montemayor et al., 2022). In general, there is consensus that organic systems can achieve better results per land FU (unit of cultivated area), mainly due to restrictions on the type and amounts of polluting inputs (energy, fertilizers, pesticides, etc.). However, results per mass FU (i.e., kg or t) could be the opposite, as noted above, for many agricultural systems (Meier et al., 2015; van der Werf et al., 2020; Montemayor et al., 2022). These results were often attributed to the productivity of the studied systems, which is strongly affected by certain characteristics of the cropping system. In fact, productivity in woody crops may vary depending on the planting density, cultivar used, the amounts of inputs applied and the type of chemicals permitted (Pergola et al., 2013; Ben Abdallah et al., 2021; Coppola et al., 2022). These specific characteristics, among others, are often not adequately considered in comparative LCAs between organic and conventional farming systems, when setting the goal and scope and analyzing the inventory (Meier et al., 2015). For a more accurate analysis and fair comparison, the systems should have similar characteristics and comparable production values.

The absolute footprint values shown in this study for organic and conventional production are substantially higher than in other fruit production systems using conventional water resources (e.g., Pergola et al., 2013; Ribal et al., 2017; Bonales-Revuelta et al., 2022). For example, the carbon footprint of grapefruit production in this study ranged from 195 to 249 kg CO_2eq t^{-1} vs. 36 to 123 kg CO_2eq t^{-1} for orange production in Mexico (Bonales-Revuelta et al., 2022). The use of DSW notably increased the environmental impact of the irrigation stage (Fig. 3), due to the high energy consumption for RO at the desalination plant. The high energy (and hence environmental) cost of RO desalination (Fayyaz et al., 2023) has been well reported in LCA studies (Aziz and Hanafiah, 2021).

The post-treatment of DSW for deboronation further escalated the footprint, particularly when using the RO BRT. A recent study by Najid et al. (2021) detailed the environmental issues of boron rejection for RO DSW production at desalination plant level. Currently, a second stage for reducing the boron concentration to below crop tolerance levels (lower than 0.5 mg L^{-1}) is performed in coastal desalination plants in other regions of the world (Gorenflo et al., 2007; Hilal et al., 2011; Güler et al., 2015). However, this has yet to be implemented in most desalination plants in south-eastern Spain, and hence the need to perform on-farm deboronation, as indicated above. The IX technology has been shown to have a much lower impact in the selected categories than RO; the average difference was 89 %. In addition, the on-farm deboronation cost with IX was reported to be lower than with RO (0.23 vs. 0.33 € m^{-3}, Imbernón-Mulero et al., 2022b). Najid et al. (2021) highlighted that the main limitations of IX technology are waste disposal and resin regeneration. Other BRTs such as electrodeionization could avoid the use of chemicals, but to date this technology has not been applied on an industrial scale.

In order to curb the footprint of irrigation with DSW, the use of renewable energy sources for DSW production has shown promising results (Raluy et al., 2006; Biswas, 2009; Najjar et al., 2022). This also applies to RO BRT, which is highly pollutant due to its energy requirements. Najjar et al. (2022) evaluated scenarios with different energy sources for the operation of a seawater RO desalination plant, which consisted of a combination of fossil fuels and renewables (wind-grid, photovoltaic-grid, and anaerobic digestion-grid). All those combinations showed significant environmental improvements in all the scenarios, with the best results being for the wind-grid energy. Although renewables are expected to replace conventional energy sources, mostly fossil fuels, by 2050 (IRENA, 2018), the deployment of these sources still faces challenges related to high economic costs and uneven geospatial distribution (Aziz and Hanafiah, 2021). Therefore, the combination of clean and conventional energy, particularly anaerobic digestion-grid combinations, has been suggested for footprint mitigation in parts of the world where full reliance on a single source poses significant challenges (Najjar et al., 2022).

The present case study combined multiple aspects that are currently relevant for policy making in order to curb environmental issues derived from intensive agriculture. The obtained results could provide guidance for the design of policies to improve the environmental sustainability of DSW use in agriculture in general, and in citriculture in particular, which requires further boron removal from DSW. For the latter, the selection of sustainable technological alternatives for the seawater boron removal stage is crucial to avoid aggravating the environmental impacts of the use of DSW for agriculture. Finally, the work should be extended to the economic and social dimensions, which are often seen as competing with environmental interests and whose interdependencies should be taken into account (Parra-López et al., 2023).

5. Conclusions

The current work evaluated and compared the life cycle environmental footprint of organic and conventional production of grapefruit irrigated with desalinated seawater. The comparative assessment included the on-farm deboronation process of DSW using two technologies (RO and IX). This study compared systems with similar agronomic characteristics (e.g., cultivar and planting density), in order to provide a fairer Life Cycle Assessment between organic and conventional production. To the best of our knowledge, this is the first comparative LCA for the two grapefruit systems and the two on-farm BRTs of DSW. The main results of this study were:

- The organic grapefruit system showed better environmental performance than the conventional system in all impact categories and in both land and mass FUs (ha and t). The most environmentally friendly system of the studied scenarios was organic production combined with the use of IX for deboronating DSW. Irrigation with DSW, RO for boron reduction, and fertilizers were the stages with the highest impacts in the studied scenarios.
- IX had a much lower (at least one order of magnitude less) environmental footprint than RO in all categories. The DSW treatment was the LCA phase with the highest impact for both technologies. In particular, electricity was the process with the highest contribution in RO, and chemicals were the main impact factors in IX.

Further studies should address other technological alternatives, especially those based on renewable energy sources and minimal use of chemicals. Furthermore, zero liquid discharge systems, which allow the treatment of rejected water to recover valuable resources, such as fresh water, minerals or energy (Panagopoulos et al., 2019), should be included to mitigate the footprint of the water treatment. Finally, the analysis should be extended to the economic and social dimensions in order to provide a complete sustainability result. Life cycle sustainability assessment could be used for that purpose.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.05.023.

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