Agricultural Water Management 286 (2023) 108407

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

The sustainability of desalination as a remedy to the water crisis in the agriculture sector: An analysis from the climate-water-energy-food nexus perspective

Babak Zolghadr-Asli [a,b,*,1], Neil McIntyre [a,c], Slobodan Djordjevic [b], Raziyeh Farmani [b], Liliana Pagliero [a]

[a] *Sustainable Minerals Institute, The University of Queensland, Brisbane, Australia*
[b] *Centre for Water Systems, University of Exeter, Exeter, UK*
[c] *The School of Civil Engineering, The University of Queensland, Brisbane, Australia*

ARTICLE INFO

Handling Editor - Dr. B.E. Clothier

Keywords:
Desalination
Irrigation
Water resources management
Water crisis
Climate-water-energy-food nexus

ABSTRACT

Over the years, desalination has become integral to water resources management, primarily in coastal semi-arid to arid regions. While desalinated seawater has mainly been supplied to municipal and high-revenue industries, the agriculture sector faces increasing irrigation demands, making it a potential user. This review assesses the sustainability of using desalinated seawater for irrigation, shedding light on its limitations and potential. Using desalinated water for irrigation presents challenges, including its high energy consumption, potential contribution to climate change, and agronomy-related concerns. However, evidence suggests that these challenges can be addressed effectively through tailor-fitted strategies. That said, conventional binary decision-making paradigms that label practices as good or bad and focus on a singular, isolated aspect are insufficient for evaluating the sustainability of desalination due to the complex and interconnected nature of the issues involved. To overcome this, the climate-water-energy-food (CWEF) nexus concept is proposed as a comprehensive framework for sustainability assessment. Adopting the CWEF nexus approach allows for a better understanding of the potential challenges associated with using desalinated water for irrigation, encompassing social, economic and environmental concerns. To ensure effective management of these challenges, it is crucial to tailor desalination projects to specific regional conditions and employ either prophylactic or corrective strategies. By embracing the CWEF nexus approach, informed decisions can be made regarding the future utilization of desalinated water for irrigation, contributing to broader sustainability goals.

1. Introduction

While recently gathered data suggest a notable decline in worldwide fossil fuel production, these resources, most notably oil and coal, are still dominating the energy market by a considerable margin. It is estimated that fossil fuels accounted for more than 81 % of world energy production in 2019, similar to the value reported in 2018 (IEA, 2021). In addition to the adverse environmental impacts of resorting to these resources due to greenhouse gas (GHG) emissions, the alarming dependency on fossil fuels signals a developing energy crisis as these resources are, by nature, non-renewable. All in all, continuing this trajectory would create devastating future socio-economic and environmental problems.

On the other hand, global hunger levels remain alarmingly high, and the world continues to struggle with an ongoing food crisis. It is estimated that in 2021, nearly 193 million individuals faced the challenges of acute food insecurities and required immediate assistance across 53 countries/territories, a tragic all-time high record that captures the sheer magnitude of the impending food crisis (FSIN, 2022). Given the stresses on the global food system, the frequency and severity of the said crisis are expected to rise in the upcoming years (Puma et al., 2018).

Lastly, an ongoing water crisis has been looming over the world for quite some time now. One of the most notable roots of this problem is that the global water demand has been steadily increasing over the years

---

* Corresponding author at: Sustainable Minerals Institute, The University of Queensland, Brisbane, Australia.
E-mail addresses: b.zolghadrasli@uq.net.au, bz267@exeter.ac.uk (B. Zolghadr-Asli).
[1] ORCID: 0000-0002-3392-2672.

https://doi.org/10.1016/j.agwat.2023.108407
Received 9 February 2023; Received in revised form 6 June 2023; Accepted 7 June 2023

and is expected to continue the said trajectory (Ritchie and Roser, 2017). Of course, one should consider that water is not distributed evenly throughout the globe, leaving some regions with less accessibility to readily available water resources. As a result, regions such as the Middle East have been struggling with an ongoing water crisis, which is expected to be exacerbated by the adverse impacts of climate change (Bozorg-Haddad et al., 2020).

The looming crises raise challenges for the agriculture industry. As stated, the challenge of reliable food production, most notably in semi-arid and arid regions, coupled with the ever-increasing demand for new food products, drives the industry to expand its operations including extended use of water for irrigation (Valipour and Singh, 2016). Doing so would pressure the already vulnerable water sector. Furthermore, accessing new water resources can be an energy-demanding procedure that may induce further stress on the energy sector (Kenway et al., 2011). Climate change is projected to complicate the situation even further, as not only does it directly impact the agriculture sector, but it can also affect and be affected by solutions to the water and energy crises (Zolghadr-Asli et al., 2019). This situation is direr in semi-arid to arid regions, where lack of water has already taken its toll on the water, food, and energy sectors.

In light of all these crises, over the years, desalination has emerged as a reasonable practice to secure water resources, most notably in semi-arid and arid regions. By convention, desalination is defined as the *process of removing dissolved solids, such as salts and minerals, from water* (Kucera, 2019). In addition to its prominent role in augmenting water resources, what distinguishes desalinated water from other conventional alternatives is that it can buffer natural hydro-climatic volatility, making water resources management relatively independent from the hydrological cycle. As such, desalination has been playing a vital role in the current landscape of water planning and management, including and perhaps most notably, meeting municipal water demands since the 1960s (Angelakis et al., 2021).

For the most part, on a global scale, use of desalinated water in the agriculture industry has been limited. As such, while a good deal of experience and knowledge has been accumulated collectively about applying desalination to meet municipal demands, the same cannot be said about application to the agriculture sector. In fact, at the moment, based on currently available data, the only countries committed to this practice under a nationwide and publicly supported program at a notable scale are Spain and Israel (Martin-Gorriz et al., 2021). The application of desalinated water in the Spanish agriculture sector dates to 1995 when a private desalination plant was installed to guarantee the irrigation requirements of the Mazarrón Irrigation District (Martínez-Alvarez et al., 2018). In 2004, however, the Spanish government committed to a long-term plan to invest in desalinated water for the agriculture industry (Martínez-Alvarez et al., 2018; Navarro, 2018). As for Israel, while the country had been contemplating using desalinated water for irrigation since the mid-1960s, 2006 marks the milestone in which the nation committed to a long-term plan to support this practice (Lahav and Birnhack, 2007). That said, it should be noted that given current circumstances and projected challenges in the water and food industry, other regions, including Australia, Chile, China, Egypt, Saudi Arabia, and the United States, are entertaining the idea of implementing desalination for the agriculture industry (Lattemann et al., 2010; Martínez-Alvarez et al., 2018).

In light of the impending crises stated earlier, it is critical to understand the potential role of desalination in the agriculture industry, in particular for irrigation purposes. Significant relevant research has been undertaken in the last decade or so to shed light on this subject (e.g., Burn et al., 2015 Martínez-Alvarez et al., 2016; Kumar et al., 2018). Notwithstanding the necessity and value of such research, what is lacking in such analyses is the acknowledgement and, in turn, exploration of the multifaceted nature of the problem. Furthermore, any attempt to investigate this topic without exploring the impacts of climate change is arguably moot. With this in mind, through the concept of the climate-water-energy-food (CWEF) nexus, the current review aims to provide a fresh and more holistic approach to interpreting the role of desalination within the context of the agriculture industry. Similar to the well-established water-energy-food (WEF) nexus, the underlying concept of the CWEF nexus is to emphasize the interconnectedness of water, energy, food, and, in this case, climate security. This paradigm of thinking has played a vital role in contemporary sustainable water planning and management (e.g., Duan et al., 2019; Qin et al., 2022). CWEF-based frameworks have been used to evaluate the merits and drawbacks of water management techniques (e.g., Sun et al., 2020; Ren et al., 2022). This can ultimately help decision-makers and engineers better understand the nexus and what the future may hold should large elements of the agriculture industry resort to desalination as a new water resource. Ultimately, this review aims to explore how sustainable desalinated water can be within the context of the agriculture industry, which from this point onward, exclusively refers to the irrigation practices that rely on desalinated water unless explicitly stated otherwise.

2. Role of desalination from the water resources angle

In order to evaluate the potential future role of desalination in the agriculture industry, it is crucial to understand its current role in water resources management. Generally speaking, the practice of desalination has been expanding steadily on a global scale. As can be seen in Fig. 1, the industry is showing a steady growth both in terms of installed desalination plants and overall capacity. That said, because water resources and socio-economic conditions vary from region to region, so has the development of desalination projects. As can be seen in Fig. 2, the Middle East region (47.5 %) alone accounts for the majority of available global capacity for desalination, with North America (14.9 %) and southern and western Europe (10.0 %) being the next biggest investors.

As well as varying between regions, the reliance on desalination varies drastically from one sector to another. Based on Kucera (2019), Fig. 3 depicts each sector's relative share of desalinated water globally in 2015. The municipal (60 %) and industry (28 %) sectors are by a considerable margin the most notable users. These uses dwarf irrigation-related water demands, which account only for 2 % of desalinated water globally. Given the ever-increasing water demands of the agriculture sector and the ongoing water crisis, one can surmise that these numbers are going to change. As such, it would not be unexpected to see more countries incorporate desalinated water in their agricultural systems, similar to previous developments in Spain and Israel. However, as we will explore in the upcoming sections, some pressing matters, most notably environmental and economic concerns, could potentially delay or halt such long-term commitments.

3. A closer look at desalination from the energy sector perspective

The water and energy sectors are interconnected on various levels to the point that addressing the issues of one sector without at least considering the other sector is impossible (Zolghadr-Asli et al., 2019). While water is actively contributing to the energy sector, for example through fuel extraction and processing operations, thermoelectric cooling and hydropower generation, the energy sector is providing power to run the water sector. Extraction, distribution, conveyance, and wastewater collection and treatment are merely examples of how the water sector relies heavily on the energy sector (Saleh et al., 2019).

The reliance of water supply on energy supply is particularly pronounced in the desalination industry. The energy demands of desalinated water relate to how and where it is used, with additional pre- and post-treatment processes generally required to ensure water quality standards can be met, and in some cases pumping of the product over considerable distances and elevation gains is also required. Studies suggest that, on average, desalination requires four times as much

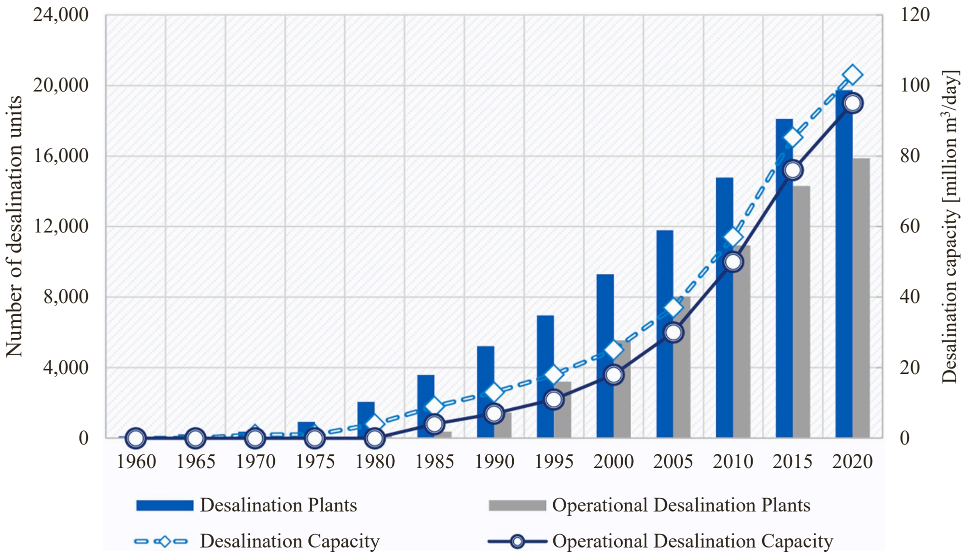

Fig. 1. The evolution of the desalination industry across the globe over the years (based on Angelakis et al., 2021).

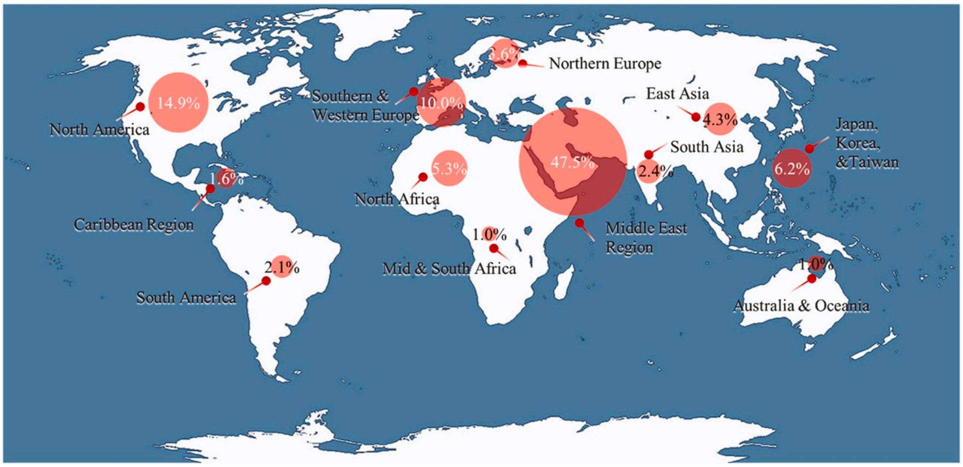

Fig. 2. Relative regional share in capacity for desalination (based on Lattemann et al., 2010).

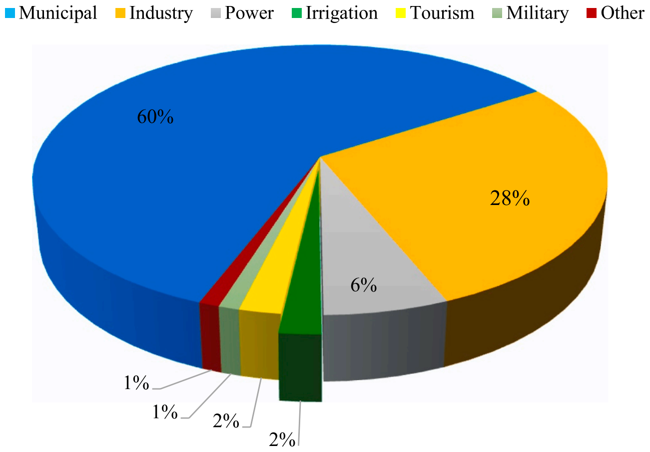

Fig. 3. The relative share of each sector from total desalinated water in 2015 (based on Kucera, 2019).

energy as water produced in water reuse plants, ten times as much energy as a traditional treatment for surface water, and nearly twenty times more energy than pumping groundwater (McEvoy and Wilder, 2012). As a result, reliance on desalination exposes water sellers and buyers to the energy market's notorious volatilities (Hussey and Pittock, 2012; Tubi and Williams, 2021). Furthermore, the energy consumption of desalinated water supply could, in turn, be ultimately reflected in GHG emissions.

In response to the economic and environmental disadvantages of desalinated water supply, there has been a gradual decline in the power consumption of desalination units over the years. Fig. 4, for instance, depicts how the power consumption of seawater reverse osmosis (RO) desalination units, currently the most relevant and efficient technology available in the market, has improved over time. The power demand for such units ranged from 10 to 16 kWh/m^3 to today's state-of-the-art RO units that require approximately 3–5 kWh/m^3 (Baten and Stummeyer, 2013; Palmer, 2015; Kim et al., 2019). Ideally, the ultimate goal would be to cut down the energy consumption of the desalination units as much as possible. It should be noted, however, that there is a minimum theoretical limit as desalination is fundamentally energy demanding. Based on thermodynamic principles, for instance, the theoretical energy requirement for an RO unit that desalinates seawater with total dissolved solids of 35,000 ppm and with temperature 25 °C, assuming 50 %

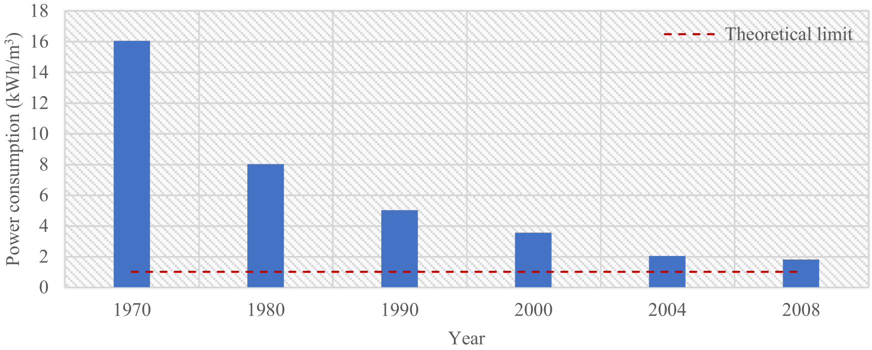

Fig. 4. The evolution in power consumption of RO desalination units over time, excluding any pre- and post-treatment procedures (based on Baten and Stummeyer, 2013; Palmer, 2015). Note The theoretical energy requirement here corresponds to the desalination of 35,000 ppm of seawater at 25 °C with 50 % energy recovery (1.06 kWh/m^3).

energy recovery, is approximately 1.06 kWh/m^3 (Baten and Stummeyer, 2013; Palmer, 2015). The stated value is, of course, based on pure theoretical conditions, and in practice, often, we cannot achieve this level of efficiency. Furthermore, incorporating pre- and post-treatment measures to enhance water quality for a specific sector would increase this power consumption. In the agriculture sector, this may include reducing the concentration of phytotoxic elements such as Boron and Chloride or reintroducing nutrition elements back to the water. Based on data gathered in Spain and Israel, such additional power consumptions are estimated to range between 0.50 and 0.77 kWh/m^3, which brings the total energy consumption of state-of-the-art large seawater desalination units that supply the agriculture sector to somewhere between 2.9 and 4.3 kWh/m^3 (Martínez-Alvarez et al., 2018).

From a planning and management perspective, a practical approach to reducing energy consumption of the desalination process is to optimize its planning, design, layout, and operation. For instance, knowing that larger desalination units can be more energy efficient (Martínez-Alvarez et al., 2019), having a clear long-term plan about water requirements, including possible expansion to include the demands of different parties and perhaps even different sectors, while planning and designing these systems can help increase their overall energy efficiency. It should also be noted that a significant amount of energy infrastructure and water supply infrastructure is required to power desalination and transport water in and out of the desalination units (DeNicola et al., 2015). As such, optimally locating the units with respect to the water source and the end user can significantly reduce both capital cost and energy requirements. Maintenance of the system is another way to uphold energy performance of these units over their operation horizon (Lapuente, 2012; Cornejo et al., 2014; Leon et al., 2021).

Nevertheless, the most notable principal factor determining a desalination unit's energy consumption is the core technology used for the desalination process. Since thermal process-based technologies such as multi-effect desalination (MED) and multistage flash (MSF) fundamentally require large amounts of thermal energy, RO is often cited as the most energy-efficient technology (Leon et al., 2021). Incorporating energy recovery devices (e.g., isobaric chambers and positive-displacement pumps), in general, is another alternative that can ultimately help offset the overall energy consumption of desalination units (Lapuente, 2012; Cornejo et al., 2014; Leon et al., 2021). Recent advancements in the desalination industry may also open the door to a whole new approach for energy-conservative desalination. Though still in the testing phase, state-of-the-art technologies such as nanomembranes or batch desalination may be the key to a more efficient process (Palmer, 2015).

A complementary way to address the challenges associated with the energy consumption of the desalination industry is to take a critical look at the energy supply, that is, employing a more environmentally friendly and possibly cheaper energy resource. Reportedly, global use of renewable energy has experienced a 3 % increase in 2020, while demand for all other fuels has declined (IEA, 2021). It was estimated that the share of renewable energy resources in global electricity generation in 2020 was around 29 % (IEA, 2021). While renewable energy resources are markedly perceived as more environmentally friendly than fossil fuels as they have less GHG emissions, they are considered to be expensive for large-scale industrial applications. This notion has been challenged recently (Pistocchi et al., 2020). Studies show, for instance, that commercial implementation of renewable energy to run large-scale desalination units could be considered economically feasible, should fossil fuel subsidies be removed from the equation (Baten and Stummeyer, 2013). Currently, the most notable practical attempts to address this issue take advantage of a hybrid format where both fossil fuels and renewable energy alternatives are simultaneously used to power a desalination unit (Tubi and Williams, 2021).

Many options are available for linking renewable energy sources and desalination technology. Scalability, costs, suitability to specific climatic and environmental conditions, and feedwater quality are the main factors that help decide the most fitting option. The most common renewable and carbon dioxide-free energy resources implemented in the desalination industry are geothermal, nuclear, solar, wave, and wind (Kucera, 2019). Among these options, currently, solar-based desalination is the most prevalent. The relative predictability of sunshine makes this option easier to plan and manage than alternatives like wave or wind power (Leon et al., 2021). Furthermore, it is becoming progressively more affordable to implement at larger scales (Pistocchi et al., 2020).

Though it has been under development since 1982, wind energy is mainly used to power relatively small-scale RO units (Kucera, 2019). Similarly, wave energy is usually paired up with small-scale RO desalination units (Palmer, 2015). Naturally, the latter approach is deemed more suitable for near-coastline cities, for example it has been employed in Perth, Australia (Palmer, 2015). Nuclear energy can also be used as a carbon dioxide-free energy source (Belessiotis et al., 2010). Often this is paired with thermal desalination technology, and it is estimated that by doing so, one can reduce the GHG of the desalination process by up to 90 % (Kucera, 2019). Geothermal energy is another renewable energy source that can directly power a thermal desalination unit or indirectly provide the electricity needed for RO units (Kucera, 2019). Similarly, solar power can be coupled with thermal desalination units using solar stills, solar multi-effect humidification (MEH), or concentrating solar plant–multi-effect distillation (CSP-MED). The other option is to convert solar radiation into electric energy using semiconducting materials in the form of photovoltaic (PV) panels (Rothwarf and Böer, 1975), with photovoltaic reverse osmosis (PV-RO) and photovoltaic electrodialysis (PV-ED) being the two main approaches. While these are considered to be promising technologies, one of the known drawbacks of PV-based desalination is the high cost of PV cells and batteries for electricity storage (Kucera, 2019).

All in all, replacing conventional resources with desalinated water in the agriculture sector, solely from the energy side of things, may impose additional challenges, including economic and environmental concerns. That said, there seem to be some strategies that can mitigate or perhaps resolve these issues altogether. Substituting fossil energies with renewable and carbon dioxide-free energy resources, for instance, can be a game-changer for the sustainability of irrigating with desalinated water. With these in mind, it is time to evaluate the practice of desalination within the context of the food and agronomic sector. It should be noted that the scope of this review was limited to the application of desalinated water for agronomic purposes and, more specifically, the irrigation of crops due to its immense role as one of the primary food supplies around the world. As such, from this point onward, the terms agriculture and agronomy solely refer to crop farming and the practice of irrigation, unless explicitly stated otherwise.

4. A closer look at desalination from the food and agronomy sector

When it comes to implementing desalination technology to meet agricultural water demand, the most significant incentive is the opportunity it provides to expand agronomical activities and, in turn, increase food production. In light of the ongoing food production deficiency, markedly in semi-arid and arid regions, this in and of itself could be a compelling-enough argument to at least entertain this idea. Despite this, relying on desalinated water for irrigation purposes is a more limited practice but has been attracting more attention in the last two decades. As a result, some of the mid-to-long-term impacts of this practice are still unclear. That said, reportedly, this practice could cause some concerns and has done so in some cases. Broadly speaking, the potential agronomic concerns are lack of essential nutrients, phytotoxicity of chemical components such as Boron (B), Chloride (Cl), and Sodium (Na); risk of soil sodicity, and low alkalinity and buffering capacity of the said water (Martínez-Alvarez et al., 2016). These potential issues could be, in turn, reflected in the crop quality, crop yield, and plants' disease resistance. However, the potential for such impacts depends on multiple factors and ultimately needs to be determined on a case-by-case basis.

Before diving into the agronomic concerns about irrigating with desalinated water, it is essential to appreciate why such concerns could arise in the first place. Often the desalinated water from RO units is associated with a total dissolved solids concentration (TDS) below 250 mg/L, very low hardness and buffering capacity, and an acidic pH (Martínez-Alvarez et al., 2016). These conditions are not quite suitable for most agricultural-related applications and can even be aggressive towards the materials used in the distribution and conveyance systems (Martínez-Alvarez et al., 2018). The general quality of the feedwater and desalination technology dictates the chemical composition of the desalinated water. That said, predominate minerals in desalinated water are Na and Cl ions, with a very low concentration of other elements such as Calcium (Ca), Magnesium (Mg), Sulfate (SO_4), as well as high concentration of Boron (B) (Martínez-Alvarez et al., 2016). While some of these elements can potentially cause phytotoxicity at high concentrations, the concentrations in water treated by RO tend to be so low that it lacks the nutrition components necessary for the plant growth and productivity. What is also crucial to note here is that desalination not only removes the undesirable minerals from the feedwater but also somewhat separates most minerals with an ionic charge, some of which have nutritional value for the plants. Furthermore, elements with no ionic charge, such as B, found with high concentrations in seawater, would easily pass the membrane with little to no filtration. Therefore, determining the agronomic impacts depends on the quality of the desalinated water relative to alternative sources. For instance, studies revealed that using desalination could be agronomically beneficial in a region in Israel, where generally, the quality of water that was replaced with desalinated water was relatively poor (Martínez-Alvarez et al., 2016). Other studies arrived at the opposite conclusion for a region in southeast Spain, where the conventional resources used prior to desalinated water were of high quality (Martínez-Alvarez et al., 2018).

The relation of crop growth to quality of the source water also depends on type of irrigation practice, local climate, soil condition, and crop type. Crop type is a crucial factor that determines how a given plant would react to desalinated water. Fig. 5, for instance, shows how different plants would generally react to B and salinity. Soil type is another key factor, for instance, soils with high clay content are more prone to sodicity hazards (Martínez-Alvarez et al., 2018). The irrigation practice is another element that needs to be taken into consideration. Cl and Na, for instance, can cause a more pronounced problem should one use sprinkler irrigation, as these elements can be absorbed directly through the leaves, markedly during periods of high temperatures and low humidity (Bernstein, 1975). Hydro-climatic conditions of a region can also be a decisive factor. For instance, higher feedwater temperature would result in a higher B passage rate (Martínez-Alvarez et al., 2016). Higher precipitation rates, as another example, can enhance the tolerance for salinity in the irrigation water, as the soil in such regions is exposed to a natural leaching process (Martínez-Alvarez et al., 2018).

All in all, desalinated water, solely from the agronomic side of things, appears to be a suitable choice to meet the ever-increasing water demands of the agriculture sector. That said, resorting to desalinated water for irrigation could have adverse agronomic side effects, varying from one case to another. This sheds light on the importance of regional and even local studies on the agronomical impacts of desalination. However, it is essential to note that observing the full effect of such practice on crop quality and yield may take a while, as was demonstrated by Silber et al. (2015). However, before reaching the overall verdict with regard to the permissibility of desalination in the context of the agriculture industry, it is crucial to look at the last piece of the puzzle, which is how this practice would influence and be influenced by climate change.

5. Climate change and desalination

There is staggering scientific evidence to prove that human activities have altered global climate over the years, most notably a steady upward trend in the global average temperature with a rate unprecedented in the last two millennia (IPCC, 2021). In fact, thanks to the recent advancements in paleoclimate data assimilation, new studies were able to demonstrate that, indeed, one of the primary drivers of the global temperature variability within the last 24 millennia was GHG emissions (Osman et al., 2021). Through tampering with the hydrologic cycle, climate change is altering the status quo of water resources worldwide. That said, how these alterations are manifested varies from region to region (Zolghadr-Asli, 2017). With that in mind, the general perception about the advent of these new hydro-climatic patterns is that these changes may exacerbate the situation of water resources in semi-arid and arid regions, including the Middle East, which, needless to say, are already experiencing mild to severe water stress (Bozorg-Haddad et al., 2020). Forming a sustaining *adaptation* strategy has become one of the last lines of defense to ultimately secure the integrity of water resources (Enayati et al., 2021; Zolghadr-Asli et al., 2021). In current context, this introduces the question, can desalination be genuinely seen as an adaptive strategy against the impacts of climate change?

Addressing this question requires us to capture the dynamic and intricate relationship between desalination and climate change. As stated, desalination is, in essence, an intensive energy-driven technology to augment conventional water resources (Heihsel et al., 2019). Notwithstanding the positive contribution of this practice to remedy the water and food crisis, the fact that it is energy-intensive implies that it can exacerbate global climate change. A common approach to understanding how desalination, or any human activity, can contribute to climate change is to measure its cumulative GHG emission. To that end, scholars employ a metric called *carbon footprint equivalent*. The carbon

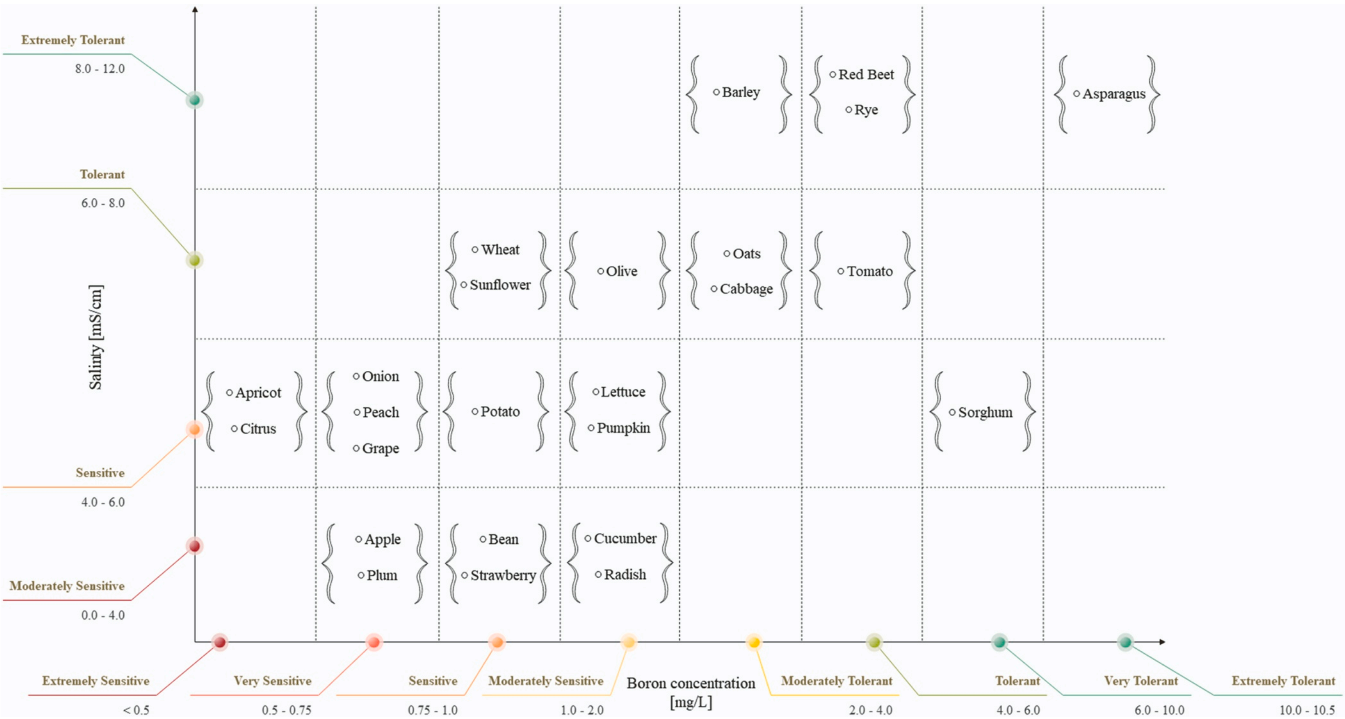

Fig. 5. The general reaction of different plant types to Boron concentration and salinity (based on Galvani, 2006 & Martínez-Alvarez et al., 2016).

footprint equivalent of an activity, often denoted by CO_2*eq*, is defined as the global warming effects of all the GHG emissions of that activity (Cornejo et al., 2014; Saleh et al., 2019). Note that the CO2*eq* metric reflects both direct emissions, say on-site sources, and indirect GHG contributions associated with the activity, such as off-site energy production, production of raw materials, and chemical components, and fuels. For a more detailed review of this subject, interested readers are referred to Cornejo et al. (2014).

In the context of climate change, using the concept above, each practice can be labeled as either a *source* or *sink* of GHG emission, where the former contributes to amplifying climate change effects while the latter subtracts or mitigates such impacts. The mainstream perception concerning the overall contribution of crop farming is that it can be seen as a sink of GHG emissions (Martin-Gorriz et al., 2021). The implication is that this industry is, in and of itself, an adaptive way to alleviate the impacts of climate change. That said, introducing desalinated water for irrigation purposes could drastically change the narrative, as the practice of desalination is generally a source of GHG emissions and, as such, can counterbalance the positive contribution of the agriculture industry.

The impact of desalination on the agriculture industry's GHG emission seems to vary from one case to another (e.g., Martin-Gorriz et al., 2021). Recent studies, however, suggest that generally, most plant-based agricultural practices can still be regarded as a sink for GHG emissions, despite the negative impacts of desalination. That said, theoretically, this practice can also present some potential nuances, as desalination creates an augmented and reliable water source with often acceptable quality that can be used to expand the farmed areas or initiate new irrigation projects with more environmentally suitable and economically profitable crops.

Theoretically speaking, how and to what extent desalination can influence climate change is rooted in a series of factors, including but not limited to desalination plant type, pre-and post-treatment process, irrigation practice, system efficiency in terms of distribution, and conveyance, desalination plant size, construction, maintenance, and operation of the system, source and demanded water quality, and hydro-geographic conditions (Lyons et al., 2009; Fine and Hadas, 2012; Cornejo et al., 2014; Saleh et al., 2019). Crop type is another decisive factor (Martin-Gorriz et al., 2021). Recent studies have illustrated how the type of crop can switch the irrigation from a sink to a source for GHG emission (Martin-Gorriz et al., 2021). Perhaps the most notable contributing factor is the energy source that fuels the entire process (Baten and Stummeyer, 2013). As explored earlier, the transition into renewable energy-based desalination plants could substantially reduce the carbon footprint of this practice, making it practically a zero-carbon footprint source for water resources (Pistocchi et al., 2020).

While the above narrative shows how desalination can influence climate change, there is another side to this, as climate change can also alter how desalination is perceived and practiced worldwide. The most obvious and arguably predominant demonstration of this is rooted in how climate change alters the hydro-climatic status quo. The common perception is that climate change is exacerbating the water crisis in semi-arid to arid regions (e.g., Bozorg-Haddad et al., 2020; Mubeen et al., 2022). As the demand for a new reliable, and sustainable source of water increases, impacted societies would be more receptive toward the idea of desalination. This has previously been observed to varying extends in Australia, Israel, Spain, and the United States (Feitelson and Rosenthal, 2012; Williams, 2018; Tubi and Williams, 2021). Some authors have even gone as far as saying that such shifts may have substantial geopolitical implications in the future, creating a new socio-political establishment that leans more heavily on coastal areas (Wolf, 2009).

On the other side of the spectrum of climate change impacts is flooding, which is projected to become a more frequent and intense phenomenon. This would, in turn, be induced as an additional source of risk to desalination infrastructure that needs to be accounted for. Often located near the shorelines, desalination networks could also be exposed to additional risks as climate change projections signal a significant rise in sea levels (DeNicola et al., 2015; Tubi and Williams, 2021). Furthermore, recent studies illustrated that the impacts of Tsunamis are expected to be more devastating due to such projections for sea level rises (Sepúlveda et al., 2021), another risk that could jeopardize the safety of coastal desalination infrastructure.

Last but not least, it is also crucial to note how the latest projections for climate change indicate that this phenomenon is adversely affecting marine life, making this ecosystem more fragile than ever (Poloczanska et al., 2013). This becomes exceptionally important within desalination practice, as improper brine and sludge disposal could further amplify these vulnerabilities. The outlook for the dynamic relationship between desalination and climate change is depicted in Fig. 6.

All in all, this section goes to show that climate is another potential factor that can influence and be influenced by the practice of desalination. However, the precise nature of this interaction is determined by various factors and, as such, requires to be studied on a case-by-case base.

6. Desalination sustainability reinterpretation within the context of climate-water-energy-food nexus

While previous sections demonstrated the potential for the application of desalinated water to irrigation, they also shed light on some of the drawbacks of this practice. Thus far, gathered experience shows that while any of the issues stated earlier can cause significant problems if not addressed correctly and in a timely fashion, they are still, for the most part, manageable. That is to say, they are practical strategies available that can mitigate, or even wholly address these negative impacts. Naturally, the applicability of these strategies would need to be determined on a case-by-case basis. However, evaluating the effectiveness and suitability of these strategies would require a more comprehensive perspective that looks beyond conventional thinking. Exploring this topic and, in turn, evaluating these strategies can be done under the umbrella term of the climate-water-energy-food (CWEF) security nexus.

Simply put, the core idea here is that there is a complex interdependency and intertwined network between the water, energy, food, and climate to the point that securing one would not be practical without addressing or considering other components (Zhang et al., 2018). As a result, a robust and sustainable planning and management paradigm often hinges on the CWEF security nexus (e.g., Rasul and Sharma, 2016; Enayati et al., 2021; Zolghadr-Asli et al., 2021). Similarly, achieving sustainability within the context of incorporating desalinated water for irrigation purposes would require a decision-making paradigm that accounts for the CWEF security nexus.

The decision to evaluate the practice of using desalinated water for irrigation under a CWEF nexus-based decision-making paradigm stems from the inherent complexity and interconnectedness of its components (Serrano-Tovar et al., 2019). By introducing desalinated water for irrigation, water deficits can be alleviated, facilitating agricultural growth and increased food production. However, this comes with the trade-off of heightened energy demand, leading to higher operational costs and potential exacerbation of climate change through greenhouse gas emissions. As discussed earlier, utilizing desalinated water for irrigation purposes can help mitigate these adverse effects through selection of the right crop or opting for renewable energy resources (Martin-Gorriz et al., 2014; Caldera and Breyer, 2019). Conversely, climate change itself can impact water availability and agricultural productivity due to its influence on the hydro-climatic cycle. This abstract example highlights the necessity of comprehensively understanding and evaluating these intricate interactions to make sustainable decisions with long-term effects.

Generally speaking, we have categorized strategies towards sustainable use of desalination for agriculture into two main classes,

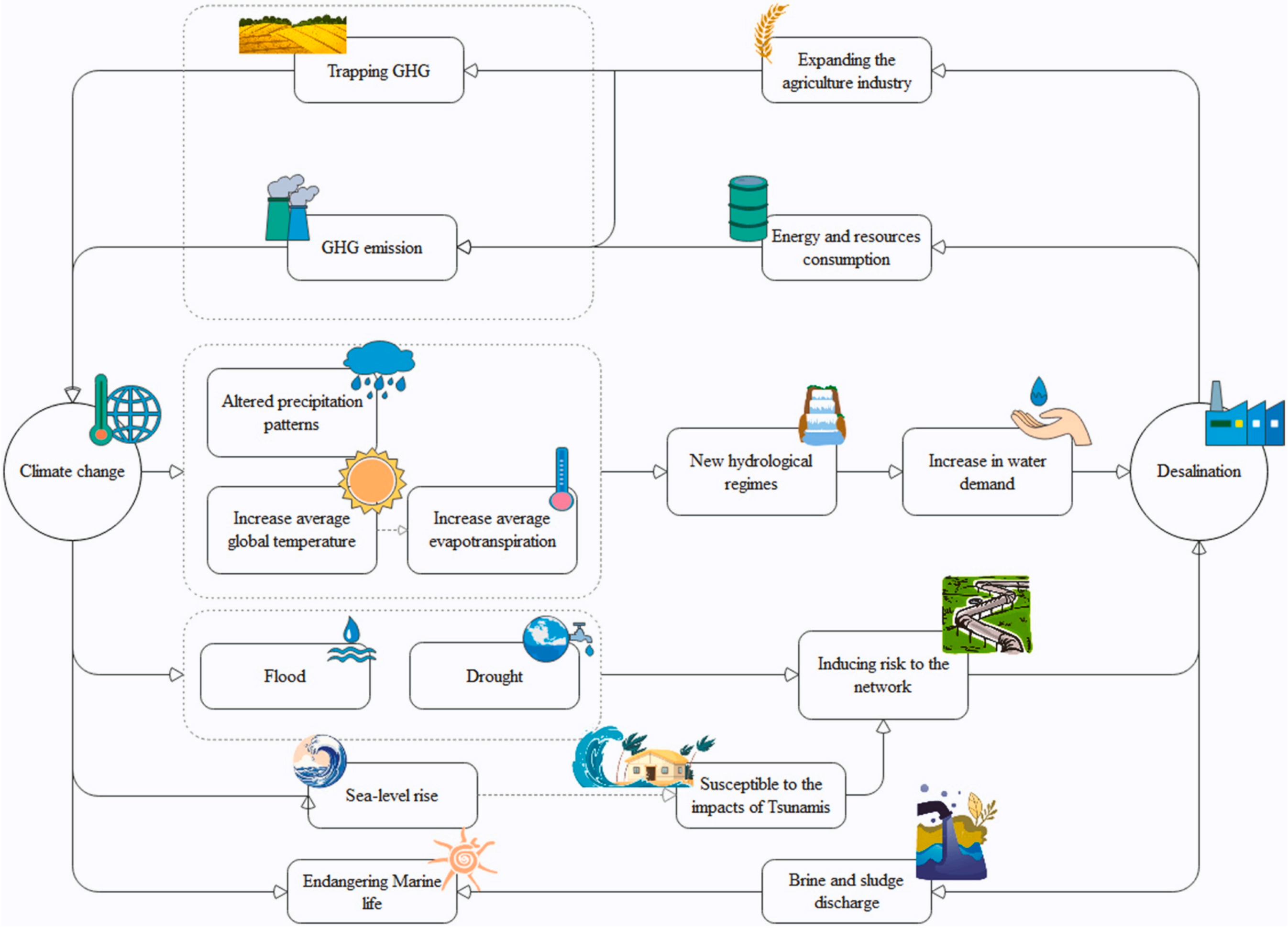

Fig. 6. Thematic outline of how desalination and climate change could potentially influence one another.

namely, prophylactic and corrective strategies. Strategies in the former category tend to prevent the problem before any meaningful impact appears. These strategies are based on carefully tailored planning and management decisions that help optimize the system for specific conditions based on regional factors. The idea is that the design, layout, and operation of desalination units, and the desalination project in general, could be customized to take advantage of unique environmental and local factors. Opting for a suitable desalination technology, project site, incorporating a cost-effective energy source, operating the system on the most suitable time slots to reduce the pressure on power grids, or selecting the best environmentally friendly way to intake and discharge water are a few examples of passive strategies. Creating a monitoring and regular maintenance plan is another prophylactic approach to getting the best performance out of desalination units.

Socio-economic-oriented strategies can also be seen as a prophylactic approach to addressing inherent problems of using desalination for irrigation purposes. As stated, for instance, one of the most pressing issues when it comes to desalination, in general, is that it is often considered a much pricier alternative, markedly in less developed regions, than most conventional water resources (Lattemann et al., 2010; Pistocchi et al., 2020). As such, expanding the application of desalinated water to agriculture may not be attractive because there is less immediate urgency than for municipal supplies, and the profit margins are far less lucrative than some industrial applications. However, revisiting the issue from a CWEF security nexus angle would bring a whole new dimension to the urgency of this situation. While it is true that the profitability of this practice, at least on a local scale, may not be able to compete with conventional resources, it is also crucial to factor in the agriculture industry's role in the context of impending water and food crises. The idea is that maintaining a consistent source of food production in the agriculture industry is becoming more difficult as time goes by. Establishing a subsidy mechanism would help desalination for the agriculture sector become more luring as an economically formidable option (Pistocchi et al., 2020). It is also important to note that, solely from a socio-economic standpoint, incorporating desalinated water for irrigation could be lucrative as it can bring a new source of revenue to the community by creating new job opportunities or increasing the income of previously established ones. With that in mind, based on a trickle-down economy school of thought, a public-funded tariff on desalinated water could balance things toward making this technology enticing enough for the agriculture industry, similar to the situation in Saudi Arabia for urban use (DeNicola et al., 2015), or Spain at a limited scale for irrigation purposes (Lapuente, 2012; Monterrey-Viña et al., 2020; Ricart et al., 2020).

Nevertheless, in light of the CWEF security nexus, establishing an effective subsidy requires careful planning that also accounts for the environmental impacts of the energy sector. The point is that conventional energy sources can be a significant source of GHG emissions, not to mention that the volatility of the energy market could cause even further complications. Investing in renewable energy as an alternative to power desalination units, entirely or in a hybrid form, could be a practical approach to mitigate the environmental impacts of desalination.

An outside-the-box alternative socio-economic strategy would be to bring forth the concept of *water markets*. The core principle here would be to look at water, or energy for that matter, as tradable economic entities as a way to offset both economic and/or environmental costs that are generally associated with the practice of desalination. As such, each stakeholder, in this case, irrigators, would be entitled to a certain amount of desalinated water. These rights could then be traded among the stakeholders or sold to interested parties from other sectors. These trades would be a mechanism for the irrigators to concentrate production in the most profitable locations and crops and reduce the environmental impacts by focusing the transfer of desalinated water to fewer sites. Trading the right to desalinated water, such as the practice that has been executed in Southeast Spain on a very limited scale (Martínez-Alvarez et al., 2016; Aznar-Sánchez et al., 2017), could be a creative way to mitigate the problems of desalination in the context of the agriculture industry.

Resource recovery, also referred to as *seawater mining,* is the process of extracting valuable minerals from the seawater. Some scholars are of the opinion that resource recovery has the potential to offset the economic cost of desalination by introducing a new source of revenue that can be gained from selling these minerals (Diallo et al., 2015; Quist-Jensen et al., 2016; Loganathan et al., 2017). As a result, resource recovery can be technically seen as a passive socio-economic strategy to accommodate the high cost of desalination. The problem from a practical standpoint is that the available options for extraction are either monetarily high value yet with very low concentration (e.g., Au, Ag), high concentration yet low financial value (e.g., sea salt), or low concentration with intermediate value (e.g., Cu, Li) (Pistocchi et al., 2020). Perhaps some potentially viable candidates from an economic standpoint would be Mg, K, and B, which often have relatively high monetarily value and concentration, though even mining these elements at least with current technology, would not be economically justifiable for all cases (Pistocchi et al., 2020). All in all, it is often hard to generalize this strategy's economic value as it requires evaluation on a case-by-case basis. Logistic matters, local markets, and the intake seawater quality are among the many factors that dictate the financial appeal of this strategy.

In addition to the prophylactic strategies, one could opt for a more hands-on approach to tackle these problems. The general theme in corrective strategies is to devise a tailored procedure to tackle a specifically targeted problem. Corrective strategies can be classified into two major classes, namely on-site and off-site strategies.

There are three main categories when it comes to on-site-oriented strategies which are pre-treatment, in-unit, and post-treatment plans. The purpose of pre-treatment regimens is often to enhance the intake water quality to a minimum pre-required condition, which is necessary to uphold the overall performance of the desalination unit. Removing solids from intake water is the most common pre-treatment regimen. In-unit strategies' basic idea is to enhance the performance or efficiency of the desalination unit, often in terms of energy consumption or improving the desalinated water quality. Incorporating energy recovery (e.g., isobaric chambers and positive-displacement pumps) is an effective active strategy to offset the overall energy consumption of desalination (Lapuente, 2012; Cornejo et al., 2014; Leon et al., 2021). In some cases, the chemical composition of the intake water contains a higher concentration of components that could be harmful to specific sectors. For instance, a common issue with utilizing seawater desalination for irrigation is the high concentration of phytotoxicity elements such as B, Cl, and Na) (Martínez-Alvarez et al., 2018). Using multi-pass RO is often a practical yet energy-taxing way that has proven to help reduce the concentration of these elements to acceptable and harmless levels (Martínez-Alvarez et al., 2016, 2018). Finally, if need be, the post-treatment regimens are there to either minimize the adverse environmental impacts of desalination or enhance the quality of the desalinated water cost-effectively. In the former case, a standard course of action is imposing more rigorous physical or chemical restrictions, say using multi-pass RO, to enhance the quality of brine discharge, which could mitigate the known negative impacts of desalting units on ecosystems and marine life. Another post-treatment regimen for incorporating desalinated water for irrigation is reintroducing nutrients that are often lacking in desalinated water. As a post-treatment process, these minerals, most notably Mg, Ca, and SO_4, could be reintroduced to the desalinated water, which can reinvigorate the said resource for agricultural purposes (Ben-Gal et al., 2009).

In contrast to on-site treatment regimens where a corrective course of action would be selected at the desalination management level, in off-site strategies, the consumers, whether individually or perhaps collectively, proactively attempt to make the desalinated water more suitable to their specific requirements. Within the realm of the agriculture sector, the two known examples of these strategies are mixing different water resources to create a more suitable batch on-site and adding fertilizers to account for lacking nutritional elements in desalinated water. Considering the often-high cost of desalination, in addition to improving the water quality for irrigation purposes, the former strategy could also help reduce the overall cost of irrigation with desalinated water. This, however, requires an on-site monitoring system that tracks the chemical composition of desalinated water and an additional facility to mix the said water with the right proportion.

As was shown here, evaluating the pressing issues of desalination individually would not be sufficient, and may be an ineffective approach to resolving or mitigating the disadvantages of desalination. Reinterpreting these problems within the context of the CWEF security nexus can, however, help justify the implication of desalination for agricultural purposes by shedding light on some hidden yet crucial angles of the problem. All in all, experiences in the past suggest that most if not all these problems are, for the most part, manageable if addressed in a proper and timely manner. This means that if the right course of action is selected for a specific problem, it is possible to maintain these adverse impacts to an acceptable level. However, the crucial thing to note here is that multiple factors often come into play, making it rather impossible to render a solution acceptable for all cases and situations. In other words, like most water management problems, a universally optimum solution may not exist, and the best strategy must be determined on a case-by-case basis.

7. Concluding remark

With the looming threats of water and food crises, it is crucial to rethink how water resources management needs to adapt to emerging challenges. Desalination is an established way of alleviating the challenges of increasing water demand in the municipal sector, primarily in semi-arid to arid regions where water availability is a pressing problem. Gradually, other sectors have started to adopt desalination as technological advances have made it more cost-effective, while the associated environmental issues have become better understood and better managed. The agriculture sector has tentatively started to use desalinated water for irrigation purposes. Following the footsteps of Israel and Spain, incorporating desalinated water for irrigation could become an enticing idea in the future, as more regions started to entertain the idea of utilizing this resource in the agriculture industry.

While the outlook of this strategy, in general, seems to be positive for the most part, there are some pressing issues when it comes to utilizing desalinated water for irrigation purposes. For one, this technology is, by nature, energy-intensive, which, in turn, makes this not quite enticing from an economic standpoint compared to conventional sources of water. The other problem here is the GHG emissions associated with the energy consumption of this technology. In addition to endangering the marine ecosystem and possibly spoiling the structure of the irrigated soil, perhaps the most pressing environmental issue behind expanded use of desalination for irrigation is its potential role in exacerbating climate change.

All in all, understanding how sustainable desalination can be in the context of the agriculture industry requires investigating and, in turn, mitigating these adverse impacts. Doing so, however, would not be possible through conventional assessment frameworks, as this is by nature a multi-faceted problem, as it would effectively influence society in various ways. This, more than anything, goes to show that when it comes to desalination, it might be time to abandon and move on from this outdated, and arguably misleading *binary* perception about this practice. Rather the concept is multi-dimensional, intricate, and intertwined with so many aspects of our modern-day life. As such, it might be borderline impossible to summarize or limit the impact of such practices by simple labels of being *good* or *bad*. As was demonstrated here, reinterpreting this matter under the umbrella of the CWEF security nexus would perhaps provide a more realistic and applicable idea about the merits and drawbacks of this technology within the context of the agriculture industry. Reevaluating the performance of desalinated water for irrigation purposes using the CWEF security nexus would unveil that, while there are indeed issues in this practice that require to be addressed promptly and adequately, the potential contribution of this technology lies in the bigger picture of its contribution to the food, water and climate change crises. One should note that over the years, different mitigation strategies have been proposed to mitigate the adverse impacts of desalination. These are either prophylactic in nature or tend to have a more corrective approach. In light of the CWEF security nexus, selecting the right combination of these strategies can be a practical way to mitigate these problems on a case-by-case basis.

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.

Data Availability

No data was used for the research described in the article.

References

Angelakis, A.N., Valipour, M., Choo, K.H., Ahmed, A.T., Baba, A., Kumar, R., Wang, Z., 2021. Desalination: from ancient to present and future. Water 13 (16), 2222.

Aznar-Sánchez, J.A., Belmonte-Ureña, L.J., Valera, D.L., 2017. Perceptions and acceptance of desalinated seawater for irrigation: A case study in the Níjar district (Southeast Spain). Water 9 (6), 408.

Baten, R., Stummeyer, K., 2013. How sustainable can desalination be? Desalin. Water Treat. 51 (1–3), 44–52.

Belessiotis, V., Papanicolaou, E., Delyannis, E., 2010. Nuclear desalination: a review on past and present. Desalin. Water Treat. 20 (1–3), 45–50.

Ben-Gal, A., Yermiyahu, U., Cohen, S., 2009. Fertilization and blending alternatives for irrigation with desalinated water. J. Environ. Qual. 38 (2), 529–536.

Bernstein, L., 1975. Effects of salinity and sodicity on plant growth. Annu. Rev. Phytopathol. 13 (1), 295–312.

Bozorg-Haddad, O., Zolghadr-Asli, B., Sarzaeim, P., Aboutalebi, M., Chu, X., Loáiciga, H. A., 2020. Evaluation of water shortage crisis in the Middle East and possible remedies. J. Water Supply.: Res. Technol. -AQUA 69 (1), 85–98.

Burn, S., Hoang, M., Zarzo, D., Olewniak, F., Campos, E., Bolto, B., Barron, O., 2015. Desalination techniques—A review of the opportunities for desalination in agriculture. Desalination 364, 2–16.

Caldera, U., Breyer, C., 2019. Assessing the potential for renewable energy powered desalination for the global irrigation sector. Sci. Total Environ. 694, 133598.

Cornejo, P.K., Santana, M.V., Hokanson, D.R., Mihelcic, J.R., Zhang, Q., 2014. Carbon footprint of water reuse and desalination: a review of greenhouse gas emissions and estimation tools. J. Water Reuse Desalin. 4 (4), 238–252.

DeNicola, E., Aburizaiza, O.S., Siddique, A., Khwaja, H., Carpenter, D.O., 2015. Climate change and water scarcity: the case of Saudi Arabia. Ann. Glob. Health 81 (3), 342–353.

Diallo, M.S., Kotte, M.R., Cho, M., 2015. Mining critical metals and elements from seawater: opportunities and challenges. Environ. Sci. Technol. 49 (16), 9390–9399.

Duan, W., Chen, Y., Zou, S., Nover, D., 2019. Managing the water-climate-food nexus for sustainable development in Turkmenistan. Journal of Cleaner Production 220, 212–224.

Enayati, M., Bozorg-Haddad, O., Fallah-Mehdipour, E., Zolghadr-Asli, B., Chu, X., 2021. A robust multiple-objective decision-making paradigm based on the water–energy–food security nexus under changing climate uncertainties. Sci. Rep. 11 (1), 1–14.

Feitelson, E., Rosenthal, G., 2012. Desalination, space and power: The ramifications of Israel's changing water geography. Geoforum 43 (2), 272–284.

Fine, P., Hadas, E., 2012. Options to reduce greenhouse gas emissions during wastewater treatment for agricultural use. Sci. Total Environ. 416, 289–299.

FSIN, 2022. Global Report on Food Crises 2022.

Galvani, A., 2006. The challenge of the food sufficiency through salt tolerant crops. In Life in Extreme Environments (pp. 437–450). Springer, Dordrecht.

Heihsel, M., Lenzen, M., Malik, A., Geschke, A., 2019. The carbon footprint of desalination: an input-output analysis of seawater reverse osmosis desalination in Australia for 2005–2015. Desalination 454, 71–81.

Hussey, K., Pittock, J., 2012. The energy–water nexus: managing the links between energy and water for a sustainable future. Ecol. Soc. 17 (1) https://doi.org/10.5751/ES-04641-170131.

, 2021International Energy Agency (IEA), 2021. Key world energy statistics 2021. Head of Communication and Information Office, Paris, France.

IPCC, 2021. Climate Change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

Kenway, S.J., Lant, P.A., Priestley, A., Daniels, P., 2011. The connection between water and energy in cities: a review. Water Sci. Technol. 63 (9), 1983–1990.

Kim, J., Park, K., Yang, D.R., Hong, S., 2019. A comprehensive review of energy consumption of seawater reverse osmosis desalination plants. Appl. Energy 254, 113652.

Kucera, J., 2019. Desalination: Water from Water, John Wiley & Sons, ISBN: 978-1-119-40774-4.

Kumar, R., Ahmed, M., Bhadrachari, G., Thomas, J.P., 2018. Desalination for agriculture: water quality and plant chemistry, technologies and challenges. Water Sci. Technol.: Water Supply 18 (5), 1505–1517.

Lahav, O., Birnhack, L., 2007. Quality criteria for desalinated water following post-treatment. Desalination 207 (1–3), 286–303.

Lapuente, E., 2012. Full cost in desalination. A case study of the Segura River Basin. Desalination 300, 40–45.

Lattemann, S., Kennedy, M.D., Schippers, J.C., Amy, G., 2010. Global desalination situation. Sustain. Sci. Eng. 2, 7–39.

Leon, F., Ramos, A., Perez-Baez, S.O., 2021. Optimization of energy efficiency, operation costs, carbon footprint and ecological footprint with reverse osmosis membranes in seawater desalination plants. Membranes 11 (10), 781.

Loganathan, P., Naidu, G., Vigneswaran, S., 2017. Mining valuable minerals from seawater: a critical review. Environ. Sci.: Water Res. Technol. 3 (1), 37–53.

Lyons, E., Zhang, P., Benn, T., Sharif, F., Li, K., Crittenden, J., Chen, Y.S., 2009. Life cycle assessment of three water supply systems: importation, reclamation and desalination. Water Sci. Technol.: Water Supply 9 (4), 439–448.

Martínez-Alvarez, V., Martin-Gorriz, B., Soto-García, M., 2016. Seawater desalination for crop irrigation—a review of current experiences and revealed key issues. Desalination 381, 58–70.

Martínez-Alvarez, V., González-Ortega, M.J., Martin-Gorriz, B., Soto-García, M., Maestre-Valero, J.F., 2018. Seawater desalination for crop irrigation—current status and perspectives. Emerg. Technol. Sustain. Desalin. Handb. 461–492.

Martínez-Alvarez, V., Maestre-Valero, J.F., González-Ortega, M.J., Gallego-Elvira, B., Martin-Gorriz, B., 2019. Characterization of the agricultural supply of desalinated seawater in Southeastern Spain. Water 11 (6), 1233.

Martin-Gorriz, B., Soto-García, M., Martínez-Alvarez, V., 2014. Energy and greenhouse-gas emissions in irrigated agriculture of SE (southeast) Spain. Effects of alternative water supply scenarios. Energy 77, 478–488.

Martin-Gorriz, B., Martínez-Alvarez, V., Maestre-Valero, J.F., Gallego-Elvira, B., 2021. Influence of the water source on the carbon footprint of irrigated agriculture: a regional study in South-Eastern Spain. Agronomy 11 (2), 351.

McEvoy, J., Wilder, M., 2012. Discourse and desalination: potential impacts of proposed climate change adaptation interventions in the Arizona–Sonora border region. Glob. Environ. Change 22 (2), 353–363.

Monterrey-Viña, A., Musicki-Savic, A., Díaz-Peña, F.J., Peñate-Suárez, B., 2020. Technical and agronomical assessment of the use of desalinated seawater for coastal irrigation in an insular context. Water 12 (1), 272.

Mubeen, M., Rasul, F., Ahmad, A., Wajid, S.A., Khaliq, T., Hammad, H.M., Nasim, W., 2022. Climate change-induced irrigation water problems and resolution strategies: a case study. In: Building Climate Resilience in Agriculture. Springer, Cham, pp. 179–194.

Navarro, T., 2018. Water reuse and desalination in Spain–challenges and opportunities. J. Water Reuse Desalin. 8 (2), 153–168.

Osman, M.B., Tierney, J.E., Zhu, J., Tardif, R., Hakim, G.J., King, J., Poulsen, C.J., 2021. Globally resolved surface temperatures since the Last Glacial Maximum. Nature 599 (7884), 239–244.

Palmer, N.T., 2015. Reducing carbon footprint of desalination: the australian experience. In: Recent Progress in Desalination, Environmental and Marine Outfall Systems. Springer, Cham, pp. 175–187.

Pistocchi, A., Bleninger, T., Breyer, C., Caldera, U., Dorati, C., Ganora, D., Zaragoza, G., 2020. Can seawater desalination be a win-win fix to our water cycle. Water Res. 182, 115906.

Poloczanska, E.S., Brown, C.J., Sydeman, W.J., Kiessling, W., Schoeman, D.S., Moore, P. J., Richardson, A.J., 2013. Global imprint of climate change on marine life. Nat. Clim. Change 3 (10), 919–925.

Puma, M.J., Chon, S.Y., Kakinuma, K., Kummu, M., Muttarak, R., Seager, R., Wada, Y., 2018. A developing food crisis and potential refugee movements. Nat. Sustain. 1 (8), 380–382.

Qin, J., Duan, W., Chen, Y., Dukhovny, V.A., Sorokin, D., Li, Y., Wang, X., 2022. Comprehensive evaluation and sustainable development of water–energy–food–ecology systems in Central Asia. Renewable and Sustainable Energy Reviews 157, 112061.

Quist-Jensen, C.A., Macedonio, F., Drioli, E., 2016. Integrated membrane desalination systems with membrane crystallization units for resource recovery: a new approach for mining from the sea. Crystals 6 (4), 36.

Rasul, G., Sharma, B., 2016. The nexus approach to water–energy–food security: an option for adaptation to climate change. Clim. Policy 16 (6), 682–702.

Ren, H., Liu, B., Zhang, Z., Li, F., Pan, K., Zhou, Z., Xu, X., 2022. A water-energy-food-carbon nexus optimization model for sustainable agricultural development in the Yellow River Basin under uncertainty. Appl. Energy 326, 120008.

Ricart, S., Villar-Navascués, R., Gil-Guirado, S., Rico-Amorós, A.M., Arahuetes, A., 2020. How to close the gap of desalinated seawater for agricultural irrigation? Confronting attitudes between managers and farmers in Alicante and Murcia (Spain). Water 12 (4), 1132.

Ritchie, H. & Roser, M., 2017. Water Use and Stress. OurWorldInData.org.

Rothwarf, A., Böer, K.W., 1975. Direct conversion of solar energy through photovoltaic cells. Prog. Solid State Chem. 10, 71–102.

Saleh, L., al Zaabi, M., Mezher, T., 2019. Estimating the social carbon costs from power and desalination productions in UAE. Renew. Sustain. Energy Rev. 114, 109284.

Sepúlveda, I., Haase, J.S., Liu, P.L.F., Grigoriu, M., Winckler, P., 2021. Non-stationary probabilistic tsunami hazard assessments incorporating climate-change-driven sea level rise. Earth's Future 9 (6) e2021EF002007.

Serrano-Tovar, T., Suárez, B.P., Musicki, A., de la Fuente Bencomo, J.A., Cabello, V., Giampietro, M., 2019. Structuring an integrated water-energy-food nexus assessment of a local wind energy desalination system for irrigation. Sci. Total Environ. 689, 945–957.

Silber, A., Israeli, Y., Elingold, I., Levi, M., Levkovitch, I., Russo, D., Assouline, S., 2015. Irrigation with desalinated water: a step toward increasing water saving and crop yields. Water Resour. Res. 51 (1), 450–464.

Sun, J., Li, Y.P., Suo, C., Liu, J., 2020. Development of an uncertain water-food-energy nexus model for pursuing sustainable agricultural and electric productions. Agric. Water Manag. 241, 106384.

Tubi, A., Williams, J., 2021. Beyond binary outcomes in climate adaptation: the illustrative case of desalination. Wiley Interdiscip. Rev.: Clim. Change 12 (2), e695.

Valipour, M., Singh, V.P., 2016. Global experiences on wastewater irrigation: challenges and prospects. Balance Urban Dev.: Options Strateg. Liveable Cities 289–327.

Williams, J., 2018. Diversification or loading order? Divergent water-energy politics and the contradictions of desalination in southern California. Water Altern. 11 (3), 847–865.

Wolf, A.T., 2009. A long term view of water and international security 1. J. Contemp. Water Res. Educ. 142 (1), 67–75.

Zhang, C., Chen, X., Li, Y., Ding, W., Fu, G., 2018. Water-energy-food nexus: concepts, questions and methodologies. J. Clean. Prod. 195, 625–639.

Zolghadr-Asli, B., 2017. Discussion of "Multiscale assessment of the impacts of climate change on water resources in Tanzania" by Umesh Adhikari, A. Pouyan Nejadhashemi, Matthew R. Herman, and Joseph P. Messina. J. Hydrol. Eng. 22 (8), 07017010.

Zolghadr-Asli, B., Bozorg-Haddad, O., Enayati, M., Goharian, E., 2021. Developing a robust multi-attribute decision-making framework to evaluate performance of water system design and planning under climate change. Water Resour. Manag. 35 (1), 279–298.

Zolghadr-Asli, B., Bozorg-Haddad, O., Chu, X., 2019. Hydropower in climate change. Encycl. Water.: Sci., Technol. Soc. 1–5.