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Review

Freshwater Shortage, Salinity Increase, and Global Food Production: A Need for Sustainable Irrigation Water Desalination—A Scoping Review

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Highlights:

What are the main findings?

- Climate-change-induced freshwater shortage and soil salinity have a long-term potential effect on agriculture.
- Salinity of agricultural soil and irrigation water imposes a critical barrier to food production.

What are the implications of the main findings?

- Technology-driven desalination technologies may not be feasible for the production of irrigation water.
- Alternative sustainable desalination techniques for irrigation water need to be further researched and developed.

Abstract: Climate-change-induced freshwater shortage and saline intrusion have been posing significant risks to agricultural sectors in arid and semi-arid regions, negatively impacting irrigation, crop yield, and food production. Climate-smart sustainable solutions are the requirement to combat these major concerns. To overcome freshwater scarcity, pressure-driven desalination techniques are used that require advanced operational systems and electricity, which creates an additional economic burden when applied in the agriculture sector. Therefore, more sustainable methods for soil and water desalination using plant-, microbial-, algal-, biomass-, and carbon-based systems are needed. This scoping review addresses the effects of climate change on freshwater shortage and global food production, the influence of salinity and sodicity on agriculture, and sustainable desalination technologies.

Keywords: climate change; desalination; food production; irrigation water; soil salinity

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1. Introduction

Climate change has a severe impact on water resources, agriculture, human health, flooding in coastal areas, and the ecosystem. Nearly 50 million people globally were affected by climate-related disasters in 2020 [1]. An increase in the concentrations of anthropogenic greenhouse gases is a key driver of climate change [2]. With a projected global population of 10 billion by 2050, it is imperative that we find ways to produce enough food. Moreover, the loss of ecosystems and decrease in agricultural yields due to rising temperatures can lead to food insecurity and loss of livelihoods. Hence, the efficient use of water in irrigated agriculture is crucial to ensure sustainable development, particularly due to increasing global temperatures. Using marginal water for irrigation is one of the more practical methods. One of the leading agricultural issues limiting crop production is soil salinity and sodicity [3]. In arid and semi-arid regions, irrigation is crucial for crop production and the development of agriculture [4]. In addition, accessing fresh water in most communities around estuaries is challenging due to the high salinity of nearby surface water and groundwater; therefore, brackish water must be desalinated before it can be used for agricultural purposes [5].

In water-stressed areas, the expansion of irrigated agriculture competes with expanding residential and industrial needs, potentially resulting in more water being distributed to high-priority sectors at the cost of agriculture. As food demand and water shortage rise, these complicated dynamic conditions put pressure on agriculture in many regions where conventional water sources are utilized for irrigation. Therefore, it has become necessary to explore an alternative agricultural water supply [6]. The scientific community is working on finding alternatives to current resource utilization and management due to several issues, including population growth, freshwater scarcity, food insecurity, land degradation, and climate-affected agriculture [7].

To better understand the relationship between climate change, freshwater shortage, soil salinity, and food production, this manuscript aims to review the following three topics: (i) effects of climate change, freshwater shortage, and soil salinity on global food production, (ii) conventional desalination technologies and costs, and (iii) more sustainable desalination of irrigation water in order to boost crop yield to meet the demands of the increasing population. To meet this end, the published journal manuscripts and book chapters were obtained in a systematic manner (Figure 1), mostly from ScienceDirect, Taylor and Francis, Google Scholar, and ResearchGate after keyword-based searches, such as climate change and soil salinity, climate change and food production, climate change and irrigation water shortage, desalinated irrigation water, global climate change, salinity intrusion and agriculture, salinity and sodicity, biomass, salt-tolerant crops, water hyacinth, and desalination technologies. The original search for the articles published from 2010 to present was performed. After screening the top 100 publications using all the keywords, we identified 202 research articles relevant to this study's goal. Then, after removing the duplicate copies and other irrelevant publications from this review, we were left with 70 relevant studies. More papers have been included in this study using the website connectedpapers.com and cross-referenced papers from the reviewed articles. Thereby, this review used a total of 79 references.

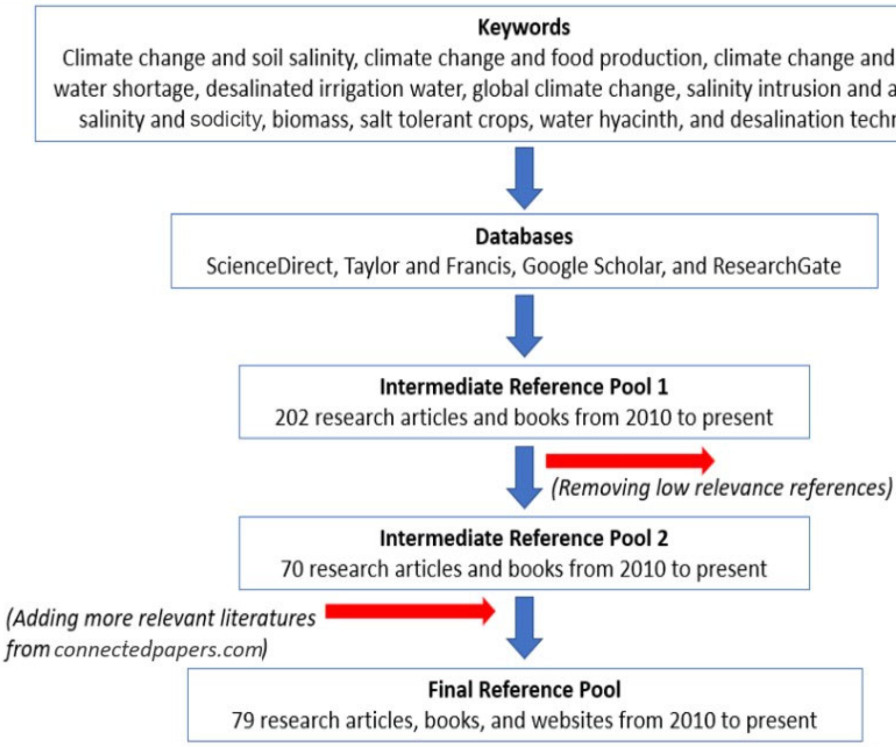

Figure 1. Flowchart of relevant literature acquisition.

2. Global Population and Food Security

The growing global population and shifting eating patterns will cause food demand to be increased dramatically in future decades, and, consequently, the global food system will face a considerable challenge [8,9]. The Food and Agriculture Organization (FAO) of the United Nations predicted that there will be a need to feed nine to ten billion people worldwide by 2050. Hence, the food output will need to be ramped up by 70% by 2050 compared to 2005–2007 to meet the rising demand, and the production in underdeveloped countries must nearly double [10]. Kumar et al. [11] also mentioned that the world will need to feed roughly 1.9 billion more people in 2050 than in 2020. Population growth and the drastic change in land use will affect the demand for agricultural produce and food production in numerous ways.

3. Climate Change and Water Shortage

Freshwater plays a major role in human development, and there is a growing problem of water scarcity around the world [12]. A study projected that four billion people will experience severe water scarcity annually for at least a month [13]. The Ministerial Declaration of the Second World Water Forum in The Hague in 2000 outlined the objective to meet water security by ensuring the protection and improvement of coastal, freshwater, and related ecosystems, promoting sustainable development and political stability, and improving accessibility to sufficient, safe water at an affordable price [14]. The availability of safe water is linked to human well-being, and water is required in every sphere of life for drinking purposes, several industrial activities, hygiene, recreation, and agriculture [15]. Hence, ensuring food security for current and future generations requires sustainable water utilization. A question that is commonly inquired about is how to enhance water productivity in order to cultivate a greater number of crops while using a reduced amount of water [16]. On the other hand, a significant factor leading to water scarcity is the unregulated pumping of groundwater for irrigation [17].

The global water demand is predicted to increase by 55%, while 25% of large cities are currently experiencing some levels of water scarcity [18]. As per the report from the National Drought Mitigation Center in July 2022, the western part of the United States experienced severe drought conditions, and it is anticipated that droughts will become more frequent, severe, and prolonged in forthcoming years. The amount of precipitation that falls each year in the Southwest United States has decreased since the turn of the 20^{th} century, whereas annual rainfall has increased across the northern and eastern parts of the United States [19]. Thus, this irregular precipitation pattern, coupled with high atmospheric temperature, will lead to the intensification of wildfires and thereby accelerate the depletion of groundwater. As a result of the heterogeneity and unequal distribution of precipitation produced by climate change, waterlogging, drought, and extreme rainfall events occur, and, subsequently, crop productivity drops drastically [20]. Khan et al. [21] also mentioned that water-related hazards and glacier surface melting are increasing water shortage for agricultural usage. Antia [22] noted that poor water management practices on farms are directly associated with water losses and decreased yields.

Numerous studies have been undertaken on the impact of climate change on water resources. For instance, the Intergovernmental Panel on Climate Change predicts that India could face the most severe impacts of rising temperatures, resulting in greater inequality and poverty. Moreover, in Yemen, an arid Middle Eastern nation with slightly over 22 million inhabitants in 2008, the prospective consequences of climate change could exacerbate vulnerability and water scarcity [23]. According to Khan et al. [21], farmers in Bangladesh face significant challenges due to the variation in river flow caused by changing weather patterns as they experience low discharge from October to April followed by high discharge from May to September. Similarly, Goh et al. [24] estimated water shortage in the Klang River basin in Malaysia and found that there will be water lacking in most months from 2046 to 2065. Furthermore, Nielsen-Gammon et al. [25] enunciated that climate change increases the likelihood of drought conditions that will worsen in many regions of the

United States. For example, 2011 was the worst year of drought in Texas, and this event cost the state 7.6 billion dollars for agriculture and livestock losses. Santikayasa et al. [26] also reported that, because of expected climate change, expanding populations, and improved living standards, sustainable water use in agriculture will face several challenges and future agricultural water management will encounter issues, such as responding to probable climate change and maintaining water use, in the future.

4. Climate Change and Increased Soil Salinity

Variation in climate patterns significantly impacts biodiversity, soil health, crop yield, and water use. Climate change has both direct and indirect effects on soil. For example, soil erosion, vegetation deterioration, and soil salinization are on the rise, posing a threat to future food security. Moreover, it is predicted that many lower terrains and settlements will be in danger from significant sea level rises, heavy rainfall, severe floods, and glacier melt if the atmosphere continues to warm promptly. Likewise, it is expected that agricultural areas will undoubtedly be submerged [27]. According to Vogel and Meyer [10], the intrusion of salt water into aquifers and the increased frequency of storm surges resulting from climate change harm food production in island and coastal regions. Eswar et al. [28] noted that the most saline soils are found in South America, Africa, and Central and North Asia. Salt-affected soils cover approximately 1060 million hectares globally, and their area is gradually increasing due to climate change. Moreover, FAO reported that, according to the estimation of the United States Salinity Laboratory and other salinity monitors, one-thirteenth billion of the world's land is now affected by salt [29]. United Nations Environment Program (UNEP) declares that, worldwide, 50% of croplands and 20% of agricultural lands are damaged by salt. Among them, 15.7 million hectares (Mha) of the area are covered in North America, 2.0 Mha in Mexico and Central America, and 129.2 Mha in South America, respectively [30].

As stated previously, an increase in average temperature causes the sea level to rise. This results in a high water table, flooding low-lying areas, and saltwater intrusion, primarily driving soil salinity. Several research studies have demonstrated the relationship between climate change variables and soil salinity. Sadik et al. [31] stated that upstream freshwater volume and ocean water impact salt levels. Due to sea level rise, climate change may speed saltwater infiltration into rich soils. Excessive groundwater extraction in arid and semi-arid regions may further increase soil and groundwater salinity. Soil salinity is a significant global concern in arid and semi-arid regions, where the limited moisture available is insufficient to dissolve the salts accumulated in the soil, posing a threat to agricultural production [32]. Mukhopadhyay et al. [33] mentioned that soil salinity currently affects around 33% of irrigated agricultural land and 20% of all cultivated land globally, and it is expected to increase at a higher rate by 2050. Furthermore, low-lying coastal areas are particularly vulnerable to rising sea levels, which can lead to saltwater infiltration and increased salt concentrations in the soil through various mechanisms, such as estuaries and rivers, high tides, groundwater inflow, and the deposition of salt-enriched soils further inland [29]. Neumann et al. [34] addressed that about 0.1 percent of the global population lives in coastal belt areas below 10 m of mean sea level and more than 0.4 percent in the range of 100 km from the shoreline, which makes up 2% of all the land globally. Therefore, as coastal agricultural land is drowned in large areas, sea level rise will eventually lead to a decline in the overall area of arable land. The infiltration of seawater can lead to decreased crop yields, soil degradation, and, eventually, the abandonment of agricultural land. For example, a rise in sea level of about 100 cm would result in flooding around 600 km^2 of agricultural fields of the Albemarle–Pamlico Peninsula on the North Carolina coast, USA [11].

Without sufficient drainage, all irrigated lands in arid and semi-arid regions will eventually become salinized. This is particularly problematic in coastal agricultural zones, particularly in areas such as the Mediterranean basin, where irrigation with saline water can significantly deplete soil resources and lead to lower crop yields. For example, Greece has abundant groundwater resources, but overuse of these resources can result in seawater intrusion, which diminishes groundwater quality. Additionally, the security of the local water supply is threatened by soil salinization brought on by seawater intrusion [35]. High levels of salinity can lead to osmotic imbalances, limiting water intake and transpiration and resulting in lower crop yields compared to what could be achieved with freshwater irrigation [36]. Despite the difficulty in obtaining exact numbers, experts agree that the salinity issue is spreading rapidly across the globe [37]. Concerns regarding salinity have been exacerbated in the United States by the pollution of irrigation drainage water with hazardous trace elements. Because of this recently discovered component, the off-site consequences of irrigation have received more attention than the on-site effects of salinization [38]. It is essential to recognize that lower-middle-income and low-income nations are more susceptible to climate change's effects [39].

Some models were developed for the mid-term (2031 to 2060) and long-term (2071 to 2100) future to predict hotspots and regions of decreasing soil salinity, referring to the data from 1904 to 1999 [40]. They considered data from the dryland areas of 30 countries across Asia, Africa, Australia, Europe, and North and South America. One of their model's results are shown in Figures 2 and 3, respectively. Based on the global circulation model, it projected continental-level salinity changes in total area (%) with EC $\geq$ 2 dS m^{-1} in the mid-term and long-term future relative to the average of 1904–1999 under different greenhouse gas concentration trajectories according to representative concentration pathways (RCP), resulting in radiative forcing of 4.5 watts/m^2 and 8.5 watts/m^2, respectively. The results indicate that, for RCP at 4.5 watt/m^2, the percentage of drylands in Europe affected by salinity decreased to 6.53% in the mid-term and 9.13% in the long-term periods. In contrast, for RCP at 8.5 watts/m^2, South America exhibited the highest levels of salinity, with 2.35% of the total arid area affected at this level. This percentage increased to 4.88% for the same region under RCP at 8.5 watts/m^2.

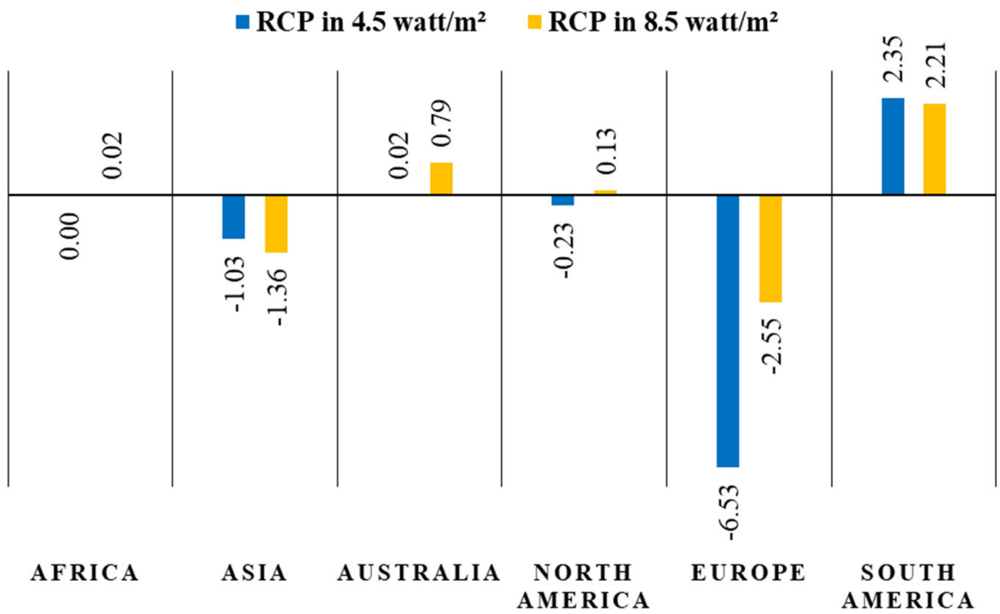

Figure 2. Continental-level salinity change in total area (%) with EC $\geq$ 2 dS m^{-1} in the mid-term (2031 to 2060) future relative to the 1904–1999 period data average (Hassani et al. [40]).

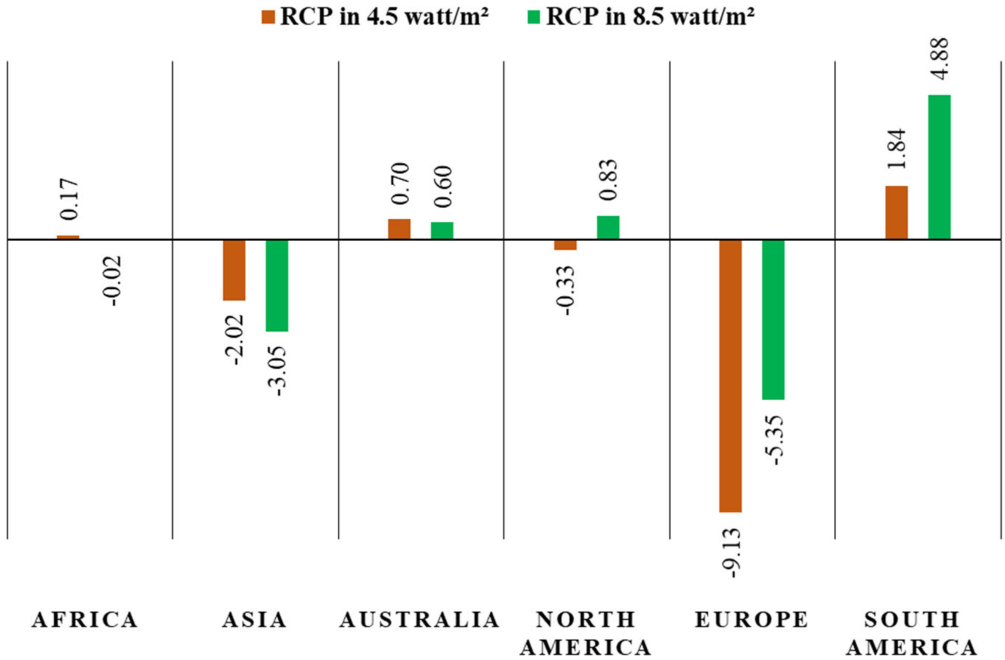

Figure 3. Continental-level salinity change in total area (%) with EC $\geq$ 2 dS m^{-1} in the long-term (2071 to 2100) future relative to the 1904–1999 period data average (Hassani et al. [40]).

5. Influence of Salinity on Food Production

5.1. Salinity and Sodicity

Soil sodicity and salinity are major agricultural issues that limit plant development and growth worldwide. The influence of soil sodicity and salinity as stress factors on plants has been studied extensively over many years [30,41]. Soil salinity refers to the abundance of dissolved inorganic salts in irrigation water, measured in either volume or weight units, which can negatively impact crop yields in an inversely proportional manner [3]. Precisely, salinization is the accumulation of soluble salts in the solum or soil rock to the degree that impacts environmental health, agricultural productivity, and economic prosperity. Salt-affected soils are present in over 100 countries worldwide and can vary in size, composition, and properties [42]. However, the composition and concentration of dissolved salts can differ depending on their source [43]. High salt concentrations can adversely affect crops by reducing the osmotic potential of the soil solution or by elevating the levels of ions such as chloride (Cl^-) or sodium (Na^+), which can harm crops in specific ways. The most frequently occurring cations and anions found in water are Na^+, Cl^-, sulfate ($SO_4{}^{2-}$), nitrate ($NO_3{}^-$), bicarbonate ($HCO_3{}^-$), calcium (Ca^{2+}), and magnesium (Mg^{2+}), respectively. In addition to the common cations and anions, high-saline water may contain other elements, such as strontium, silicon dioxide, lithium, barium, iron, etc. Soil salinity has an extremely detrimental impact on agricultural activities and is a crucial factor in soil health. The relationship between soil salinity and crop yield can be calculated using the salt tolerance equation [44]:

$$Y_r = 110 - b\,(EC_e - a), Y_r$$

where Y_r is the relative crop yield, EC_e represents the electrical conductivity of the saturatin extract (dS m^{-1}), a is the salinity threshold (dS m^{-1}), and b represents the slope expressed as % per dS m^{-1}. Soil, a non-renewable resource, can be defined as saline when EC_e of saturated soil extract at a standard temperature of 25 °C equals or exceeds 4 dS m^{-1} [45]. A comprehensive study [46] addressed that electrical conductivity (EC) is typically used to measure soil salinity, which is defined as excessive concentrations of dissolved inorganic solutes.

Salinity can be measured in terms of total dissolved solids (TDS) expressed in milligrams per liter (mg/L) or parts per million (ppm). It can also be indicated as total soluble salts in milliequivalents per liter (meq/L). For the conversion of EC to TDS, a factor of 640, and, for an extremely concentrated solution, a factor of 800, is generally used [47]. Additionally, brackish water is known to have higher salinity than fresh water but less salt concentration than seawater. It can be caused when fresh water and seawater mingle in estuaries, for example, de-icing salt application, irrigation, mining, and saline wastewater discharge [5].

On the other hand, soil sodicity can be measured by either the sodium adsorption ratio (SAR) or the exchangeable sodium percentage (ESP) of the saturation extract. It refers to the excessive sodium (Na^+) accumulation in the soil. Ezlit et al. [3] described in their comprehensive study on salinity and sodicity in irrigation that the amount of sodium in water or soil is significant because it impacts the stability of clay minerals and the likelihood of problems with dispersion, erosion, or drainage. The sodicity of water or soil is usually determined by the concentration of sodium in the solution compared to that of calcium and magnesium. The SAR of water and soil solution can be calculated as below:

$$SAR = \frac{Na^+}{\left[Ca^{2+} + Mg^{2+}\right]^{1/2}}$$

Salinity and sodicity in soil usually change with the depth of its layer. Salt typically climbs to the bottom of the root zone under irrigated conditions in sandy soils and generally proportionally in clay soils. However, when the ESP exceeds the value of 15, the soil profile is termed as sodic [33,43].

5.2. Salinity Influences on Soil Health

Pessarakli and Szabolcs [30] state that the main common characteristic of soils affected by salt is a high concentration of electrolytes. However, the degree of salinization and/or alkalization can vary, leading to differences in soil chemistry, morphology, pH, and other characteristics. The electrolyte and salt content of the irrigation water or soil are the two most critical factors affecting these soils' physical characteristics [37]. The soils with high concentrations of electrolytes and salt make up a significant portion of all the salt-affected soils in the world, and they are mainly found in arid and semi-arid regions. Salinity intrusion degrades soil health, drastically losing plant yield [3,43,48,49]. This excess salt in the soil solution can lead to osmotic stress on plants, which reduces their ability to absorb water from the soil [27]. This can cause dehydration and even death of the plant, making the seed sowing unsuccessful. Abro et al. [50] projected the global extent of saline-sodic soils to be around 560 Mha.

According to Dennis and Robers [51], the quality of irrigation water is a crucial factor that affects plant growth, productivity, water infiltration, and other physical parameters of the soil. The salinity hazard of water is the most significant factor affecting crop yield, and it can be assessed using electrical conductivity (EC). As the soil solution's EC increases, the dissolved salt concentration also increases. This results in a higher osmotic potential of the soil solution, which makes it more difficult for plants to absorb water. The increased concentration of salt ions in the soil solution can also cause toxicity to plants, leading to decreased growth and yield. In addition, high salinity can lead to changes in soil structure, reducing water infiltration and increasing the risk of soil erosion. Therefore, it is important to consider the salinity of irrigation water when selecting crops and managing soil and water resources for agriculture. MSU Extension [49] evaluated that water with an EC of less than 0.75 dS m^{-1} is generally not problematic, while water with an EC higher than 3.0 dS m^{-1} can pose serious issues. Soils with good physical qualities are crucial for high-level crop production, including appropriate permeability for water and air, and easily crumbled soil that promotes seed germination and root growth. However, these qualities tend to deteriorate on irrigated lands, leading to poor permeability and soil tilth.

5.3. Salinity Influences on Plants/Produce/Crops

According to FAO standards, "cropland" includes "arable land," which is defined as "land cultivated with short-term crops that do not need to be replanted for several years," and "permanent crops" is defined as "land farmed with long-term crops that do not need to be replanted for several years" [52]. Halophytes are plants that can survive and adapt to saltwater conditions. Halophytes can be categorized based on their salt tolerance and exclusion [33]. For reclaiming salt-affected soils, the preferred halophytes include porterasia, rhizophora, prosopis, salicornia, pandanus, panicum, pongamia, and salvadora. Negacz et al. [52] addressed the subject of saline soils' potential for food production using salt-tolerant crops. This study aimed to identify areas with the greatest potential for saline agriculture worldwide based on soil salinity, fertility, and water availability. The authors debate that moderately to severely salty soils, which are unsuitable for conventional agriculture, may be effectively utilized for saline agriculture. However, a significant proportion of these salt-affected soils cannot be used for agriculture due to poor soil fertility and limited water availability. The study found that the total surface area with the most favorable conditions for agriculture was 744,400 km^2 for irrigated agriculture and 1,779,500 km^2 for rain-fed agriculture (Figure 4). Additionally, saline agriculture could be practiced on 2,136,800 km^2 in non-depleted water basins.

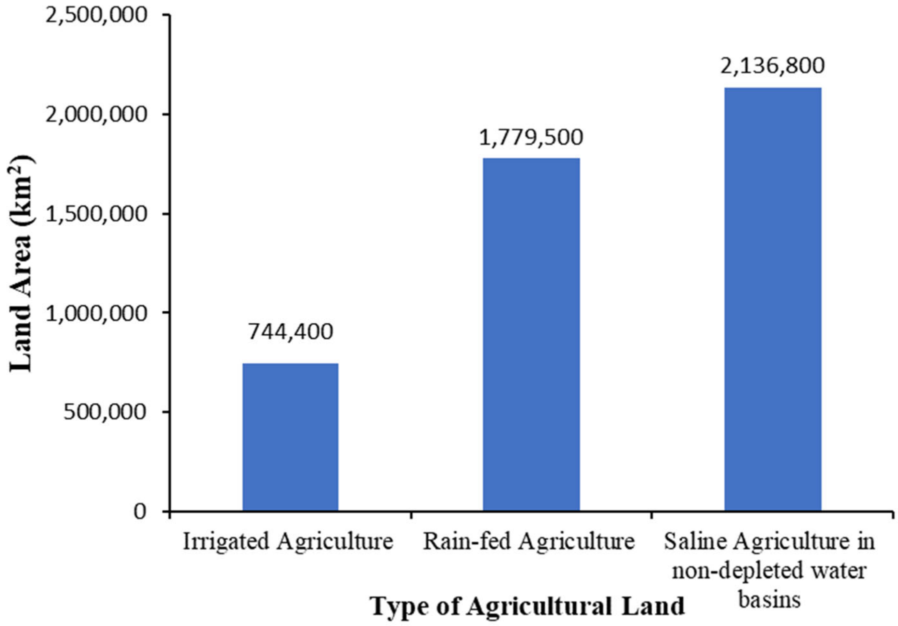

Figure 4. Globally available agricultural land (modified from Negacz et al. [52]).

According to Rhoades and Miyamoto [46] and Shahbaz et al. [53], in many parts of the world, especially in arid and semi-arid areas, there are too many soluble salts in the soil, which makes it hard to grow most crops, including vegetables. As with other crops, the amount of salt vegetables can handle varies greatly from crop to crop. For instance, cabbage, broccoli, cauliflower, eggplant, tomato, potato, radish, turnip, lettuce, cucumber, pepper, and pumpkin are said to be moderately sensitive to salt (EC less than 2.8 dS m^{-1}). Red beet (*Beta vulgaris*) is considered to have moderate tolerance to salt, while pea, okra, carrot, and onion are highly sensitive to salt, with an electrical conductivity (EC) level of 1.0–1.5 dS m^{-1}. Among common vegetable crops, tomato plants have been studied the most regarding their response to abiotic stresses, especially salt stress.

6. Reclamation of Sodic Soil

Abro et al. [50] stated that, in order to function effectively as a best management practice to increase soil health and plant and crop productivity, lowering salinity and sodicity in irrigation water necessitates a high-output treatment process. The effects of climate change on soil and groundwater salinity are considerable. As a result, climate-smart salinity management strategies may offer a variety of options for reducing salinity and its negative effects on the ecosystem. Minhas et al. [54] asserted that the salinization of soils is a major limitation to crop growth and is particularly prevalent in irrigated areas of arid and semi-arid regions. As a result, salinity development is considered one of the primary agronomic constraints hindering crop growth in these regions.

There are currently edaphic interventions and cutting-edge methods for overcoming salinity limitations and bolstering agriculture's resilience to the impacted soils. To counteract the negative impacts of salinity, there are several effective methods, such as managing to leach efficiently, utilizing both saline and freshwater appropriately, implementing suitable irrigation practices and schedules, and adopting advanced micro-irrigation systems, such as precise-leveled and drip- and flow-rate-regulated surface irrigation systems. The main aim of managing and reclaiming soil affected by salt is to recover its productivity by lowering the levels of exchangeable Na^+ ions and soluble salts to a level suitable for optimal or almost optimal plant growth. The ultimate goal is to revive the soil's capacity to sustain healthy plant growth, ensuring sustainable land use for agriculture or other purposes [55]. To achieve the objectives of restoring soil productivity and promoting healthy plant growth, it is necessary to carry out the replacement of excessive Na^+ ions from the exchange complex, as well as leach out salts below the root zone. Adequate drainage is also crucial to accomplish these goals. There are three types of methods available for reclaiming Na^+ ions: physical, chemical, and biological reclamation methods. To remove salts and improve soil permeability, physical and mechanical methods are used, such as subsoiling, deep plowing, profile inversion, flushing, sanding, and scraping. These methods can result in a temporary increase in crop growth, but there are challenges associated with disposing of the salts after the process is complete. In addition, these methods are not effective in the long term when dealing with shallow water tables where salts can accumulate on the surface due to evapotranspiration. Additionally, it has been demonstrated that plowing sodic soils with dense clay sub-surface layers with a depth of up to 100 cm is helpful [55]. Deep plowing increases crop yields due to greater water intake rates and penetration depth. This approach results in a doubling of the adequate, accessible water storage capacity of the subsurface layers. Moreover, organic matter levels in sodic soils are frequently low. In addition to reclaiming sodic soils, integrating organic materials and agricultural wastes into the soil improves and preserves soil structure, avoids soil erosion, and provides essential plant nutrients. Organic substances and plant roots increase the soil's biological activity. Organic inputs degrade and generate organic acids, raising CO_2 partial pressure. These processes increase the level of electrolytes, make calcium more soluble by mobilizing it, and lower the ESP and pH of the soil. To improve soil quality, a variety of organic additives, such as farmyard manure, crop wastes, chicken manure, and green manure, are commonly used.

FAO [56] suggests that adding gypsum and other supplements containing Ca^{2+} can positively impact sodic soils by improving them chemically. To manage and rehabilitate areas affected by soil salinity, a critical aspect is the sensitivity of plants to salt stress during the early stages of growth and development, with more tolerance to salinity observed in later stages. This factor should be considered in integrated soil, water, and crop solutions. Using higher-quality water earlier in the season or post-harvest periods can help to improve water utilization by removing salts from the root zone and improving growing conditions during the most sensitive stages. In cases of slightly/moderately sodic and saline soils, sufficient crop output can be achieved by solely implementing soil techniques that enhance organic carbon content, microbiological activity, and soil porosity.

7. Desalination of Water

7.1. Available Technologies for Desalination

The need for alternate freshwater resources has increased due to the worldwide freshwater crisis caused by increased water demand and freshwater contamination. Desalination is a useful technology for producing alternate freshwater sources from brackish or seawater for municipal, industrial, and agricultural use [57]. Moreover, desalination emerged as a crucial method in the 1960s for improving the quality of saline water for use in various parts of the world and industrial sectors [58]. Desalination technologies can be categorized into two leading groups depending on the separation mechanisms: (a) thermal distillation and (b) membrane separation (reverse osmosis) [57,59]. The basic process and disadvantages/challenges of these technologies have been briefly described in Table 1.

Table 1. Process, disadvantages, and challenges of thermal distillation and membrane separation desalination technologies.

Desalination Technologies	Basic Process	Disadvantages and Challenges	Reference
Thermal distillation (Multiple-Effect Distillation (MED) and Multi-Stage Flash distillation (MSF))	The thermal process heats seawater to turn it into vapor for fresh water and brine. After cooling, the vapor is condensed to produce fresh water.	The latent heat, constant energy needed for this conversion process, makes thermal desalination devices generally uneconomical	[12,60]
Membrane Separation (Reverse Osmosis (RO))	RO is a process that removes salts from water by applying external pressure to overcome the osmotic pressure and force water to pass through a semi-permeable membrane, leaving the salt and other impurities behind. The solution-diffusion mechanism mainly regulates the process of water transport through the membrane.	○ Fouling, scaling, and clogging ○ Pre-treatments required for high-salinity water ○ Qualified employees for maintenance and operation ○ High operational and capital costs ○ Labor, chemicals, and power make up about 87% of the total cost of the RO process	[61,62]

The RO process is capable of producing high-quality potable water by forcing water through the semi-permeable membrane at high pressure, effectively removing nearly all contaminants, including monovalent ions, such as Cl^- and Na^+. This process generates pure water permeate and a concentrated waste stream. The concentration of salt in the waste stream varies based on the recovery of the RO system. While RO can be used for concentrating organic substances, its primary use is for desalinating seawater. Compared to thermal distillation, the cost of desalination using RO technology is about one-half to one-third lower [57]. Ihsanullah et al. [63] asserted that there are plenty of desalination technologies available around the world that researchers are experimenting with to find a cost-effective method. Some hybrid desalination plants combine the use of thermal and membrane technology. In addition, several other desalination technologies are currently in use or early stages of development. These include membrane distillation, forward osmosis, electrodialysis, electrodialysis reversal, capacitive deionization, humidification–dehumidification, gas hydrates, solar stills, freezing, and various filtration techniques, such as nanofiltration, ultrafiltration, and ionic-filtration, as well as adsorption desalination. Some of the newer desalination techniques explored in Southeast Asia are charge-based, such as electrodialysis, electrodialysis reversal, and membrane-capacitive deionization.

7.1.1. Effect of Conventional Desalination Technologies on the Environment

According to Ihsanullah et al. [63], desalination is a process that requires a significant amount of energy to convert saltwater into fresh water and return the resulting brine to the ocean. In view of the recently emerging desalination operations and the expanding number of important facilities around the world, issues regarding the potentially harmful environmental implications of desalination are being evaluated. Groundwater pollution, marine pollution, energy use, land use, social effects, effects on weather and air quality, and noise pollution are some of the potential adverse environmental effects of desalination. Moreover, Ahmed et al. [64] stated that conventional desalination methods rely on a constant power supply, leading to higher energy consumption and increased greenhouse gas emissions. However, desalination can still be environmentally friendly if managed properly and used to conserve natural water sources. The concept of "greener" desalination aims to minimize the environmental effects of the process and protect natural resources to the fullest extent possible [63]. Dore [59] expressed that plant size, feedwater salinity, and energy prices are the three variables that impact the cost of desalination per unit of fresh water. Moreover, Ihsanullah et al. [63] mentioned that the increasing number of extensive desalination facilities worldwide had raised concerns about potential negative environmental effects. Direct and indirect impacts are the two primary types of environmental consequences associated with desalination. Direct impacts mainly arise from brine pollution, emissions of air pollutants (CO_2, CO), and increased energy use. Indirect impacts include construction effects, land use, and noise pollution. Ayaz et al. [65] analyzed the current status and potential environmental implications of conventional desalination technologies in their study. Their findings from the desalination projects reveal that, globally, 75 million, 140 million, and 218 million tons of CO_2 could be released in 2016, 2030, and 2040, respectively, if 6.1% of conventional groundwater resources were employed for desalination. Additionally, if 10% of groundwater resources were used, this number could increase to 485 million tons per year by 2040 (Figure 5). The authors used data from the Diplomacy Government of France.

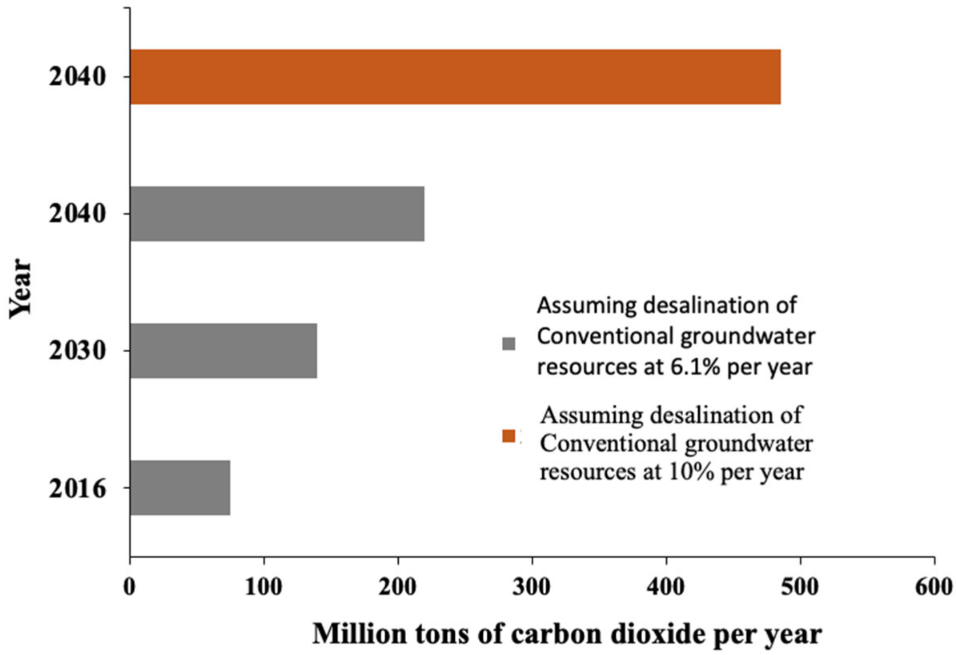

Figure 5. CO_2 emissions from conventional desalination technologies. Figure reproduced from Ayaz et al. [65] with modification under the license order number 5521460654629.

To analyze the environmental impacts of desalination technologies, a comprehensive study was conducted by Elsaid et al. [66]. For seawater desalination, RO technology causes significant physical, chemical, and biological impacts on the environment and human health. The factors are salinity, additive chemicals, such as flocculating and coagulating agents, anti-scalants, polyelectrolytes, disinfection byproducts, and heavy metals. The impact has been described below in Table 2.

Table 2. Environmental impacts due to RO seawater desalination technologies. Table reproduced from Elsaid et al. [66] with modification under the license order number 5521470667850.

Factors	Environmental Impacts
Salinity	Physical impacts Differences in density can cause convective currents, which can result in changes to the stratification of water columns. Chemical impacts ○ The salinity of the water in the receiving and mixing zone can be elevated by saline water, while the salinity of sediment can be raised by high-saline brine. ○ Reduces dissolved oxygen. Biological impacts If the salinity of seawater exceeds the tolerance level of organisms, it can lead to an increase in their mortality rate. Additionally, the growth rates and photosynthesis metabolism can also be altered.
Chemical additives	Physical impacts Turbidity may increase from suspended solids that affect the lights to penetrate. Chemical impacts ○ Unfamiliar chemicals are introduced to the aquatic environment. ○ Due to the use of Fe salts for coagulation, water loses its transparency, which affects the light to penetrate. Biological impacts Fluctuating metabolism and growth rate may occur due to the high concentration of heavy metal; also, light cannot pass through the water due to the high density. Moreover, the mortality rate of organisms can increase because of unbearable heavy metals.
Disinfection byproducts	Chemical and biological impacts Toxic substances formed from disinfection byproducts in aquatic environments result in a higher mortality rate for organisms and alterations in growth rates and metabolism due to their high toxicity.
Heavy metals	Physical impacts Turbidity may increase from the oxidation of metals that affect the lights to penetrate. Chemical impacts Density of corrosion substances may increase. Biological impacts Fluctuating metabolism and growth rate may occur due to the high concentration of heavy metal; also, light cannot pass through the water due to the high density. Moreover, the mortality rate of organisms can increase because of unbearable heavy metals.

7.1.2. Cost of Desalination

Advisian [67] stated that the cost of using multi-stage flash (MSF) distillation to remove salt from water has significantly decreased since the 1960s. Back then, it cost around USD 10 per m^3 of capacity, but, as of 2010, it costs less than USD 1/m^3 due to improved technology and decreased energy prices. Furthermore, advancements in membrane designs and integration of systems have reduced half of the cost of the desalination of salty water in the past two decades. In 2012, the Texas Water Development Board (TWDB) reported that the total cost of desalinating brackish groundwater fell within USD 0.29–0.66/m^3. While the costs of large-scale seawater RO projects appeared to have stabilized after 2005, they have fluctuated greatly since then and currently range from USD 0.79 to 2.38/m^3. Zotalis et al. [68] also pointed out that the cost reduction was also attributed to the increased size of desalination plants.

According to Ihsanullah et al. [63], the energy required for RO to produce one cubic meter of desalinated water is approximately 3–4 kilowatt hours (kwh), which includes both thermal and electrical energy. On the other hand, MSF and multiple-effect distillation (MED) require 10–16 and 5.5–9 kWh/m^3, respectively. Ahmed et al. [64] stated that electricity costs account for approximately 30% of the total cost of desalinated water using RO for seawater desalination. In a review study by Subramani et al. [69], it was found that, even if renewable energy sources, such as solar and wind, were used to power the desalination plant, the cost would be high due to the sporadic nature of their output and the large land area required.

7.2. Technologies Used for Desalination of Irrigation Water

Desalination of seawater could provide a consistent source of water for agricultural production, assisting in the solution of the global water scarcity issue. The Intergovernmental Panel on Climate Change (IPCC) has identified desalination as a potential strategy to help agriculture adapt to climate change's impacts, particularly in arid or semi-arid areas [6]. In the Middle East and India, brackish water from marginal aquifers is commonly used for irrigation, although several constraints limit the technique's potential. When the soil and water have elevated salt concentrations, it can lead to an osmotic imbalance that impedes the plant's ability to absorb water and nutrients. Consequently, crop yields may be reduced compared to those irrigated with freshwater [36]. Based on their research on the nano-filtration system, it is asserted that this technique has the potential to consume 40% reduced energy compared to the traditional RO system, decrease the current volume of extracted groundwater by 34%, and increase total crop biomass production by 18% with irrigation.

Martínez-Alvarez et al. [47] stated that brackish water desalination has been widely used in agriculture globally. Its popularity has grown in recent years due to its lower cost than desalinating seawater. Previously, desalinated seawater was deemed too expensive for agricultural purposes, but it is now being utilized for crop irrigation in Israel and Spain. RO has emerged as the preferred desalination technology for seawater due to its lower energy consumption and is believed to be the most appropriate method for agricultural applications. Furthermore, natural soil minerals and water can provide sufficient levels of essential minerals, such as magnesium, calcium, and sulfate ions, which reduces the need for additional fertilization. However, desalination removes unwanted salts and essential nutrients necessary for plant growth, resulting in lower mineral concentrations in desalinated seawater than what is required for irrigation. Therefore, using desalinated seawater for agriculture requires changes in water management systems and desalination standards, particularly if pure desalinated seawater is used. Despite this, the increasing impacts of climate change on agriculture, natural water resources, and food security are driving the adoption of desalinated seawater in areas with limited water. As desalination technology improves and the cost of desalination of seawater decreases while other water sources become more expensive, the use of desalinated seawater in agriculture is expected to continue to rise.

According to Barron et al. [7], desalinated water is being utilized in agriculture to varying amounts in different countries. Kuwait and Spain have the highest percentages of desalinated water use in agriculture for irrigation of fruit, herbs, vineyards, and olives, with 13% and 22% of their current installed capacity dedicated to farming. Saudi Arabia, which has the highest global capacity for desalinated water production, uses only 50% of that capacity for agricultural purposes. The same study found that the likelihood of desalination technology being adopted in agriculture depends mainly on the current cost of agricultural water compared to the cost of desalinated water production. In Australia, farmers are likely to pay less than AUD 1.00/m^3 for water, and, in some places, even that price is deemed too high. For example, in the southwestern region of Western Australia, the typical cost of water ranges from 18 to 50 cents/m^3. Thus, given the issues of freshwater scarcity and saltwater intrusion, it is imperative to establish sustainable desalination solutions to effectively use saline water for agricultural purposes.

8. Sustainable Salinity Management

8.1. Adsorption-Based Desalination

According to Baskar et al. [70], adsorption is the most commonly used and reliable technique for eliminating organic and inorganic pollutants from wastewater. Adsorbents that are frequently studied include charcoal, activated carbon, ordered carbon, biomass-derived polysaccharides, carbon nanotubes, graphene, ion exchange resins, and polymers. Baskar et al. [70] noted that activated carbons derived from biomass are commonly used for the removal of pollutants from water due to their affordability, substantial surface area, beneficial surface chemistry, high adsorption potential, and eco-friendly nature. When considering plant-biomass-based sorbents for water filtration, it is essential to analyze plants' functional components, porosity, and surface characteristics [71]. Earlier studies have indicated that the dried biomass from aquatic plants acts as a cation exchanger in water filtration [72]. Based on the findings of the searched articles, only a limited number of studies have focused on removing salt ions, specifically Na^+ or Cl^-, from saline water. Hettiarachchi et al. [73] found that activated coconut coir (ACC) can effectively remove 50% of Mg^{2+} and Na^+. This study produced ACC by subjecting coconut coir dust pretreated with 50% phosphoric acid to pyrolysis. Similarly, Kim et al. [74] investigated the removal of Na+ ions from saltwater using waste tea leaves, although the highest observed adsorption was only 8%. However, on treating the tea leaves with diluted acid and base, the absorption of Na+ could increase to 16%. Sagar et al. [75] used dried powder (sieved through a 500-micron sieve) of *Parthenium* sp. plant biomass at a concentration of 1 g L^{-1} wastewater solution containing 3976 ppm chloride (pH of 7) and showed a decrease in the chloride content. Similarly, the biochar made of the olive branches was applied to reduce the negative effect of salinity stress on kochia (*Bassia scoparia* L.) plants [76]. This study was conducted in Al-Huson, Jordan, and the olive tree holds the utmost importance among fruit trees in Jordan. To assess the plant's capacity to tolerate the highest salt levels, groundwater and brine water rejected from RO technology were utilized for irrigation purposes. Additionally, various amounts of biochar were incorporated into the soil to observe the effects on plant growth. The inclusion of 10% biochar resulted in various positive effects on the plants, including an increase in height by 55%, an increase in chlorophyll concentration by 121%, a rise in circumference by 76%, an enhancement in water content by 28%, and reduction in electrolyte leakage by 36%. Therefore, the olive branch biochar can significantly benefit the kochia plant to improve its salt tolerance capacity.

8.2. Plant-, Algal-, and Microbial-Based Desalination

For sodic soil reclamation, Abro et al. [50] extensively evaluated the use of *Phragmites australis* (*P. australis*) plants with four treatment methods: the gypsum at 100% soil requirement, *P. australis* plus gypsum at 50% soil-gypsum requirement, leaching (control without gypsum and plant), and only *P. australis*. This study suggests that utilizing *P. australis* alone or in combination with gypsum is an effective method for reclaiming sodic soils and reducing Na^+. *P. australis* alone demonstrated similar benefits in reducing electrical conductivity, SAR, and Na^+ concentration compared to gypsum applied at 100% soil requirement. However, using *P. australis* in combination with gypsum produced better results in terms of soil reclamation. In the plant-based adsorption or phyto-desalination, Kiridi and Zalmon [5] evaluated the salinity level of brackish water and the impact of water hyacinth on its desalination efficiency over six days. The study recommended separating the water hyacinth after three days to avoid the reintroduction of absorbed salts and proposed the introduction of new water hyacinth every three days to ensure continuous phyto-desalination until desalination is accomplished.

Several other studies have explored bio-desalination techniques by incorporating bacteria or algae into saline water. Chimayati and Titah [77] focused on the process of seawater bio-desalination, which involved the experiments of mangrove plants and bacteria over 14 days under two different levels of salinity, 15% and 25%. The plants examined in the research were *Avicennia marina* and *Rhizophora mucronate*, while the bacteria investigated were *Vibrio alginolyticus*. The study was performed in Keputih, Indonesia. When *Rhizophora mucronata* mangrove plant was combined with bacteria, the salinity removal rate was approximately 65% and 40% for salinity levels of 15% and 25%, respectively, by the 14th day of the study. Similarly, when combined with the same bacteria, *Avecennia marina* displayed removal efficiencies of around 49% and 41% for salinity levels of 15% and 25%, respectively. Further, bio-desalination of seawater and brackish water was performed using halophytic algae at the University of Texas, Austin [78]. Under regulated conditions, halophile algae, such as *Chlorella vulgaris* and *Scenedesmus* sp., were cultivated in a photobioreactor to extract NaCl salt from seawater and brackish water. The suitability of these algae for biological desalination was subsequently assessed. After the desalination and algal separation process, the removal percentages of Cl^- were determined to be 21%, 58%, and 74% for the full bloom phase, centrifuge phase, and centrifuged and filtered phase, respectively. However, two main factors that determine the effectiveness of adsorbents in real-world wastewater systems are their efficiency and cost. Additionally, the sustainable and recovery management of the adsorbents after use is a significant challenge.

9. Conclusions

The declining supply of fresh water is speedily emerging as a primary concern for both sustainable development and human existence. In addition, the global population is projected to increase to around 10 billion by 2050. Therefore, a demand for increased food production to feed the growing population will appear. However, climate change causes freshwater shortage and salinity stress to agricultural sectors. One adaptive measure to such climate-change-induced agricultural issues is reducing salinity in irrigation water and using brackish water or seawater via desalination processes. However, most of the available desalination technologies are costly and technology-driven, so they are not a plausible option for farmers. As such, more cost-effective, environmentally friendly, and sustainable desalination methods that can be used to produce irrigation water and saline soil reclamation have been researched with the use of biomass-based carbons, halotolerant plants, waste biomass, algae, and microbes.

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