agriculture

Review

Irrigation Induced Salinity and Sodicity Hazards on Soil and Groundwater: An Overview of Its Causes, Impacts and Mitigation Strategies

Aadhityaa Mohanavelu [1,*], Sujay Raghavendra Naganna [2] and Nadhir Al-Ansari [3,*]

1 Department of Civil Engineering, Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Amritangar, Coimbatore 641 112, India
2 Department of Civil Engineering, Siddaganga Institute of Technology, Tumakuru 572 103, India; sujay.gopan@gmail.com
3 Department of Civil, Environmental and Natural Resources Engineering, Lulea University of Technology, 97187 Lulea, Sweden
* Correspondence: aadhityaa65@gmail.com (A.M.); nadhir.alansari@ltu.se (N.A.-A.)

Abstract: Salinity and sodicity have been a major environmental hazard of the past century since more than 25% of the total land and 33% of the irrigated land globally are affected by salinity and sodicity. Adverse effects of soil salinity and sodicity include inhibited crop growth, waterlogging issues, groundwater contamination, loss in soil fertility and other associated secondary impacts on dependent ecosystems. Salinity and sodicity also have an enormous impact on food security since a substantial portion of the world's irrigated land is affected by them. While the intrinsic nature of the soil could cause soil salinity and sodicity, in developing countries, they are also primarily caused by unsustainable irrigation practices, such as using high volumes of fertilizers, irrigating with saline/sodic water and lack of adequate drainage facilities to drain surplus irrigated water. This has also caused irreversible groundwater contamination in many regions. Although several remediation techniques have been developed, comprehensive land reclamation still remains challenging and is often time and resource inefficient. Mitigating the risk of salinity and sodicity while continuing to irrigate the land, for example, by growing salt-resistant crops such as halophytes together with regular crops or creating artificial drainage appears to be the most practical solution as farmers cannot halt irrigation. The purpose of this review is to highlight the global prevalence of salinity and sodicity in irrigated areas, highlight their spatiotemporal variability and causes, document the effects of irrigation induced salinity and sodicity on physicochemical properties of soil and groundwater, and discuss practical, innovative, and feasible practices and solutions to mitigate the salinity and sodicity hazards on soil and groundwater.

Keywords: salinity; sodicity; irrigation; soil fertility; groundwater; bio-drainage

Citation: Mohanavelu, A.; Naganna, S.R.; Al-Ansari, N. Irrigation Induced Salinity and Sodicity Hazards on Soil and Groundwater: An Overview of Its Causes, Impacts and Mitigation Strategies. *Agriculture* **2021**, *11*, 983. https://doi.org/10.3390/agriculture11100983

Academic Editors: Helen Karasali and Evangelia Tzanetou

Received: 28 August 2021
Accepted: 4 October 2021
Published: 9 October 2021

1. Introduction

Irrigation water usually contains salts that accumulate in the soil over time, causing various problems, including plant growth inhibition, changes in soil properties, and groundwater contamination. Approximately 25% of the land (≈2000 million acres) worldwide is affected by high salt concentration, making them commercially unproductive [1–3]. Cations such as magnesium, calcium, iron, and so forth are common sources of salinity; however, the predominant cause of salinity in soils is sodium salts [4]. In arid and semi-arid areas, deposition of salts released from the parent rock, ancient drainage basins, and inland seas and a lack of proper natural drainage are major reasons for relatively higher impacts of salinity and sodicity in the region [5]. In humid areas, salinity and sodicity impacts, if any, are generally seasonal; nonetheless, the leached salts could percolate and contaminate the groundwater [6]. In the early 1930s, salinity or salt concentration was commonly expressed in terms of percentage or parts per million (ppm), and later, electrical conductivity (EC) in deciSiemens per meter, total dissolved solutes (TDS) in milligrams per liter, or total soluble salts (TSS) in milliequivalent per liter were widely used to express salinity. However, in recent times, salt concentrations are often expressed in terms of molarity units, such as millimole per liter ($mmol_c\ L^{-1}$). Sodicity, on the other hand, is described in terms of the exchangeable sodium percentage (ESP) or sodium adsorption ratio (SAR). A soil with EC greater than or equal to 4 deciSiemens per meter ($dS\ m^{-1}$) at 25 °C is said to be saline; a soil with SAR > 13 $(mmol_c\ L^{-1})^{0.5}$ is termed as a sodic soil, and soils with EC greater than or equal to 4 $dS\ m^{-1}$ and SAR > 13 $(mmol_c\ L^{-1})^{0.5}$ is considered to be saline-sodic [7,8]. Further, few researchers consider soils with lower values (6–8%) of ESP as sodic soils [4,9]. Refer to Table 1 for the classification of salinity and sodicity affected soils based on EC, SAR, and pH.

Table 1. Classification of salinity and sodicity affected soil based on physio-chemical properties (modified from Scherer, 1996 [10] and Alonge et al., 2019 [11]).

Soil Classification	Electrical Conductivity (EC, dS/m)	pH	Sodium Adsorption Ratio (SAR) $(mmol_c\ L^{-1})^{0.5}$	Description
Normal soil	EC < 4	<8.5	<13	No visible salt accumulation on soil surface, uniform crop growth.
Saline soil				
Slightly saline	4 < EC < 8	<8.5	<13	Visible salts on soil surface, patchy and uneven crop growth.
Moderately saline	8 < EC < 15			Fairly visible salt layer on soil surface, restricted and very patchy crop growth.
Strongly saline	EC > 15			Fluffy soil surface, fairly visible salt accumulation on surface, slow or no germination, patchy and highly restricted plant growth, etc.
Sodic soil	EC < 4	8.5–10	>13	Shallow plant root penetration, puddle formation with turbid water on soil surface, variability in crop growth rate, etc.
Saline-sodic soil	EC > 4	<8.5	>13	Combined characteristics of saline and sodic soils.
Degraded sodic soils	0.5 < EC < 2	5.5–8.5	>14	Contain excess exchangeable sodium and appreciable quantities of exchangeable hydrogen. ESP < 15.

Although salinity and sodicity can be detected by measuring EC and SAR or ESP, respectively, in laboratory conditions, several visual indicators can also be used to qualitatively assess salinity and sodicity of soils [12]. Some of the most common visual indicators of salinity are the formation of white crusts or stains on the soil surface; slow or no germination; reduced growth rate and patchy growth of crops; foliage, discoloration, and disfiguration of leaves; growth of halophytic plants and waterlogging [13,14]. Common visual indicators of sodicity are inhibited vegetation growth, variability in the growth rate of plants, surface ponding of rainwater (decreased infiltration), shallow plant root penetration into the soil, formation of puddles with turbid water, and difficulty in tillage [15,16]. Additionally, sodicity can also be measured in the field using turbidity tests [16].

The direct environmental impacts of soil salinity and sodicity include increased soil erosion due to decreased vegetative cover; groundwater contamination; ecosystem fragmentation; reduced weathering rates and natural release of nutrients; decreased fertility; reduced crop yield; decreased organic matter and the destruction of host-ecosystems [17–22]. The impacts of salinity and sodicity on various crop's growth have been extensively studied. For instance, sugarcane yield is closely tied with optimal soil conditions and pH; the crop yield could be significantly reduced under saline and sodic conditions [23,24].

Irrigation-induced salinity and sodicity also increases the plant water requirement due to reduced root penetration in the soil and causes overexploitation of groundwater in regions where there are no other alternative sources of water for irrigation, while in areas where surface water is used for irrigation and has a water table at shallow depths, waterlogging is generally observed [25,26]. The increase in the plant water requirement (is generally offset by increasing the duration of irrigation) to ameliorate the shunting of plant growth and to achieve optimum crop yield (growth) under saline-sodic conditions varies widely with the extent of salinity and sodicity levels, the type of crop, and soil characteristics [27]. Furthermore, apart from impacting the productivity or yield of irrigated land, salinity and sodicity also have broad implications on socio-economic growth and food security, which includes lower profit margins, poverty, and migration of farmers to urban areas in developing countries, increased fertilizer requirement, and the unlikelihood of land reclamation [28,29]. The extrapolation of global loss due to irrigation-induced salinity is roughly estimated as USD ~27.3 billion in a year caused by reduced crop production (approximating USD 441 loss per hectare of land) [30,31]. Recent studies indicate that the economic loss could be as high as USD 1604 and USD 2748 per hectare if the salinity levels rise from low to medium and medium to high, respectively, and the gross profit in undertaking any migratory measures might be too low for the farmers to adopt sustainable irrigation strategies [32]. Comparable to the above inference, a study in Australia estimated that an expenditure of AUD 65 billion over 10 years would be required to reclaim the land degradation caused by salinity and sodicity in the country [33]. Mitigation of salinity and sodicity in irrigated soils is crucial for soil conservation, socio-economic upliftment of farmers, as well as the protection of agriculture-dependent ecosystems and groundwater quality [34].

Although there are several studies in the literature that have comprehensively studied various aspects and impacts of soil salinity and sodicity on the environment (mainly soil), a systematic study analyzing the hazards of irrigation-induced salinity and sodicity on soil and groundwater is yet to be conducted [15–19,35,36]. In this paper, the causes and management (mitigation strategies) of irrigation-induced soil salinity and sodicity, as well as their effects on soil properties and groundwater (subsurface aquifers), are discussed. In addition, this overview provides a catalogue of practically feasible integrated soil fertility management practices and innovative/modern solutions to mitigate the salinity and sodicity risks to soil and groundwater.

2. Global Distribution of Irrigation-Induced Salinity and Sodicity

Accurately quantifying and identifying irrigation-induced salinity and sodicity hotspots is quite challenging because of the high geographic variability and net changes in the salinity and sodicity levels; nonetheless, certain regions mostly in semi-arid and arid regions are at higher risk because of the inherent saline and sodic nature (chemical composition) of the soil [37]. On a country scale, salinity and sodicity are pervasive in both arid and semi-arid countries throughout the world, including few humid countries such as Bangladesh and Malaysia [38,39]. Unfortunately, for most countries except Australia and the United Arab Emirates [3,40], an up-to-date national level inventory of irrigated areas affected by salinity and sodicity is not available. The most recent assessments of saline and sodic soils in several countries globally are discussed below.

In developing countries with extensive irrigated land, about one-third of the irrigated land is affected or potentially at high risk of being affected by salinity [41]. In India, about 6.73 million ha of land has been degraded due to salinity and sodicity, which were mainly catalyzed by the introduction of irrigation in western parts of the country [42]. It is also a major threat in irrigated arid and semi-arid regions of Latin America [43]. In the Pampa region of Argentina, huge volumes of saline and sodic soils (>13 million ha) exist due to poor irrigation practices leading to land degradation [43,44]. A study over Mongolia highlights a decrease in salinity in its cropping areas due to improvements in dry drainage and deployment of artificial drainage systems; however, the fallow areas are still affected by increased salinity due to long-term accumulation [45]. Salinity and sodicity are also major problems in Pakistan where about 6.3 (out of the 16.3) million hectares of its irrigated land is naturally saline-sodic, which is further exacerbated by unsustainable and inappropriate land use and management practices [46]. In Iran, 4.1 million hectares of land is affected by irrigation-induced salinity and sodicity, and the annual losses incurred is likely greater than USD 1 billion per year [47]. In central Asia, salinity affects 47.5% of irrigated land (with 95.9% of irrigated land affected in Turkmenistan, 50.1% in Uzbekistan, and 33% in Kazakhstan) and thus poses a significant threat to crop production and food security in these regions [48]. In South Africa, irrigation-induced salinity and sodicity are major threats (about 13–18% of the area under regular irrigation is affected), especially in the western parts of the country since there is severe biological degradation driven by soil organic matter decline [49]. In Russia, the majority of the irrigated lands in the southern part of the country are confined to salt-affected soils [50].

In the developed world, one-fourth of the irrigated land in the United States of America (USA) is affected by salinity [51,52]. In Colorado, USA, about 25–35% of the irrigated land (980,000 ha) is affected by saline, sodic, and saline-sodic soils, especially in the Arkansas river valley and the Colorado river basin, costing USD 750 million in economic impact [53,54]. Similarly, in North Dakota (USA), about 1.9 million and 0.7 million acres of land in 34 out of 52 counties are affected by salinity and sodicity, respectively [55]. In Europe, about 3.3 Mha. of land is affected by salinity and sodicity, of which North, Central, and Eastern Europe are significantly affected by irrigation-induced salinity and sodicity hazards [36]. Increased irrigation losses (particularly in the crop root zone), variations in the seasonal pattern of salt leaching (accumulated during irrigation) over the cultivation season, and an increase in aquifer salinity are some of the factors contributing to worsening saline-sodic conditions in Europe (notably in Italy) [36,56,57]. About 68% of the agricultural land in Australia is reported to have transient-salinity and sodicity problems (i.e., the occurrence is seasonal), while about 16% of the land is affected by irrigation and groundwater-induced salinity [4,58]. Sodicity hazard in Australia has scaled up above 60% of the cultivable land (20 million ha) even though farming is practiced without irrigation under dry conditions [9,59]. Practices such as wastewater irrigation (sewage farming) have further exacerbated the problems associated with salinity and sodicity in Australia as it significantly deteriorates the quality of soil and the integrity of the ecological systems [60–62].

3. Soil Salinity and Sodicity: Causes

The natural weathering of rocks or the parent material is the major source of salinity and sodicity in soils. Other sources include the use of saline or brackish water for irrigation, seawater intrusion in coastal areas, inadequate drainage and a rise in the groundwater table, restricted surface evaporation, and seawater sprays (moisture) near coastal areas [15,63]. Anthropogenic inputs, such as the discharge of partially or untreated industrial and domestic effluents over land, can increase soil salinity and sodicity (also referred to as secondary salinity) [64,65]. The primary source of irrigation-induced soil salinity and sodicity includes the use of fertilizers and minerals (such as gypsum, potash, etc.) and salt-intensive groundwater without adequate treatment [63,66]. Salinization is a cyclic process when, once salt water is used for irrigation, the accumulation of salt begins, increasing the water requirements of the crops, limiting leaching, and, through capillary movement and evaporation processes, leads to increased salt build-up in the soil column [67,68]. Furthermore, due to the ionic imbalance developed mainly through high sodium concentrations, soil permeability is also affected [69]. In areas with a rising water table (mainly in less irrigated drylands), high salinity is caused by restricted drainage and long-term cultivation of shallow-rooted crops (leads to salt bed formation in the soil strata), which reduces soil permeability and eventually the groundwater dissolved salts reach the surface and increases salinity [15,70,71].

In regions where water is scarce, particularly in arid or dry regions where no substitute for saline or sodic water exists, repeated usage of such water for irrigation over time leads to the salinity of both surface and sub-surface formations [72]. Such a type of salinity is often referred to as 'secondary salinity' and has severe effects on soil quality [73,74]. Management of secondary salinity is crucial because, over the past decade, most countries have been affected due to the repeated practice of using saline groundwater and fertilizers, causing salinity and sodicity to sustain or improve the agricultural yield [65,75].

4. Impacts of Salinity and Sodicity on Physicochemical Properties of Soil

Salinity greatly affects the soil pH (increases the pH above the ideal pH range of 6.5–7.5 for optimum growth in the majority of crops) and, as a result, interferes with nutrient availability for plants [76]. Some of the major plant nutrients, such as potassium, nitrogen, and sulphur, are comparatively less affected by higher pH (salinity); however, some nutrients such as phosphorus are considerably affected by salinity even at small levels (for e.g., phosphate at pH > 7.5 reacts with magnesium and calcium to form less soluble compounds) [77].

Salinity and sodicity affect the physical and hydraulic properties of soil [78,79]. Although salinity improves the stability and aggregation of soil, at high concentrations, it imposes osmotic stress on plants because soil water uptake by roots is hindered by the retention of water in the soil [80]. As opposed to salinity, sodicity leads to soil dispersion, structural instability, and swelling of aggregates [81]. The accumulation of sodium in the soil leads to a loss of soil organic carbon through carbon mineralization and also impedes the nitrogen cycle [82]. Soil dispersion is especially seen in clays due to sodicity. When the exchangeable sodium percentage (ESP) exceeds 15%, the higher concentration of sodium ions in the exchangeable soil matrix sites may result in the collapse of soil aggregates [83,84].

Salinity and sodicity also significantly reduce the hydraulic conductivity and infiltration rates, which could significantly affect the vadose zone water availability [78,85]. The irrigation water with higher SAR values > 9 can have severe consequences on the permeability of the soil depending on the type of soil and extent of surface sealing [34,86]. For example, a SAR value of 9 would create severe restrictions on permeability in textured clays; however, in the case of sandy soils, it has insignificant impacts [87]. In sodic soils, once the soil structure has collapsed, water movement through the compacted soil profile is greatly reduced, which ultimately reduces the infiltration potential of the soil [88,89].

Salinity causes the soil to flocculate, whereas sodicity causes the soil to disperse [90]. The soil stability is highly dependent on the extent of soil salinity and sodicity, which is readily determined by the salinity to sodicity ratio referred to as 'the swelling factor' [91]. The soil with a high swelling factor would have a stable soil structure, while the likelihood of soil structural problems increases as the swelling factor value decreases. Both salinity and sodicity have a combined effect on the infiltration rates (Figure 1), and the swelling factor is used to assess the potential impact of irrigation water quality on the infiltration rate. For example, soil with low salinity and high sodicity would have a severe infiltration problem [19]. Increased surface runoff and erosion potential (during rainfall) are secondary impacts on land affected by salinity and sodicity [3,19].

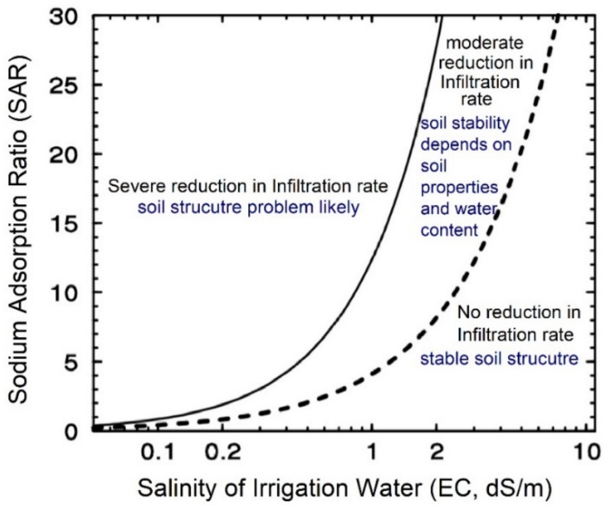

Figure 1. The relationship between soil salinity and sodicity on soil structure and infiltration (based on Hanson et. al, 1999 [92] and ANZECC, 2000 [93]).

5. Impacts of Salinity and Sodicity on Biological Activities in Soil

Biological activities, mainly the microbiological processes, which are largely concentrated in the topsoil, play a vital role in the biogeochemical cycling of soil nutrients and their availability to the plants [94,95]. The population, activity, and community structure of microbes in saline soils are influenced by the soil water potential (osmotic potential + matrix potential). Specifically, when the salt concentration in the soil solution increases, the water content reduces, leading to low osmotic potential, which makes it difficult for microorganisms to utilize the soil water content. Thus, soil salinization affects the composition of the microbial community and its metabolism, as the tolerance to low osmotic potential differs from one microbial genotype to another [96]. Highly saline soils inhibit the growth of the microbial population and enzyme activities [84,95,97], reduce carbon and nitrogen mineralization [98,99], reduce the ability of microbes (enzyme producers) that decompose cellulose [100,101], and impact soil respiration and organic matter dynamics [102–104]. Many researchers posit that fungi are less tolerant to osmotic stress (induced by salinity) than bacteria [95,96,105]. However, Rath et al. (2016) observed that the fungi growth is more resistant to salt exposure than bacteria [103]. In sodic soils, the extent of organic matter is directly related to microbial biomass carbon, soil nitrogen, and N mineralization rates [106]. The carbonate salts in saline or sodic soils complicate the carbon (C) dynamics and fluxes, which affect the microscale microbial metabolism [107]. In highly saline grassland soils, Yang et al. (2020) observed paradoxical behavior of bacterial and fungal diversity, with a relative decrease in the Proteobacteria and Firmicutes population and the abundance of the ascomycetes [108]. Some haloalkaliphilic bacteria are able to sustain and expand, even in saline environments, promoting plant growth [109]. Soil salinity was found to be a stress factor hindering biological nitrogen fixation by free-living diazotrophic microbes and heterotrophic bacteria [110]. Enzymes present in soil could also function as an indicator of saline and sodic soil fertility, and microbial amendments of soil effectively improve the fertility of the soil [111].

6. Effects of Irrigation-Induced Salinity and Sodicity on Groundwater

Salinity and sodicity in irrigated areas could be caused by a higher concentration of salts and sodium either in soil or irrigation water (either from a surface or groundwater source). Irrigation-induced salinity and sodicity can adversely affect both the chemical and the physical properties of a groundwater system through multiple and often interconnected pathways (Figure 2) that can lead to long-term groundwater contamination [6].

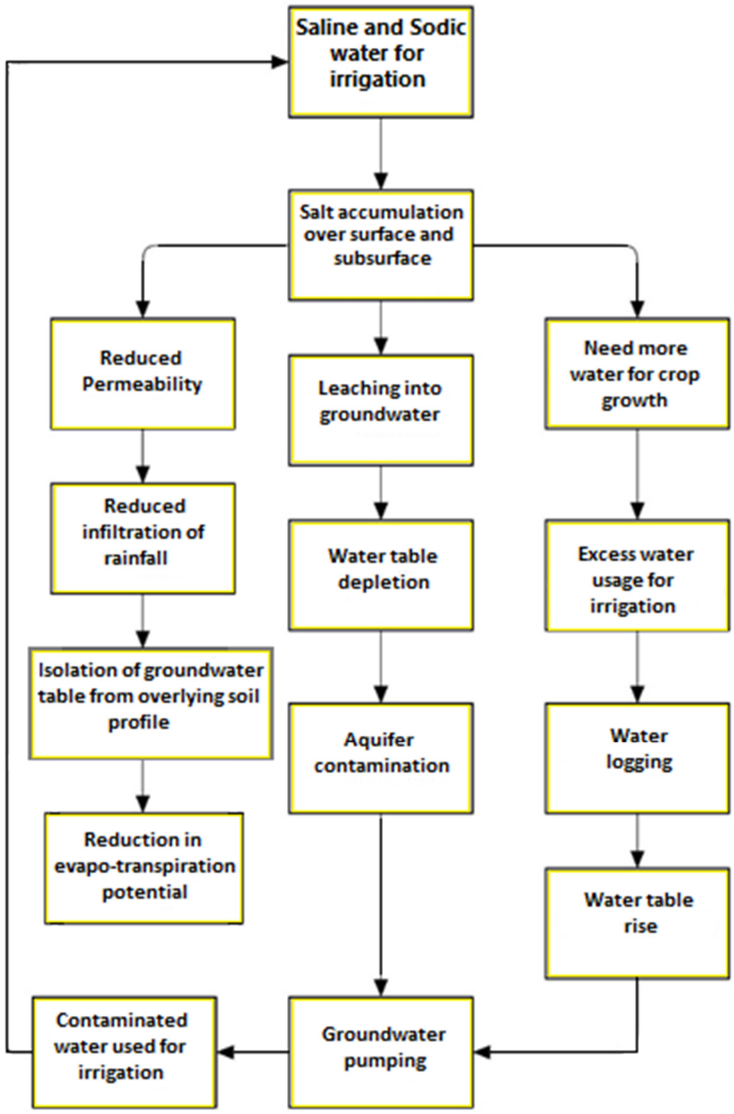

Figure 2. Effects of irrigation-induced salinity and sodicity hazards on groundwater.

When the saline- and sodic-irrigated water infiltrates and reaches the groundwater table, it first increases the water's pH and, over time, contaminates the aquifer. The groundwater salinity could further affect the water quality regionally, as connected aquifers can result in regional impacts [112]. The extent and severity of the contamination, however, could vary with the type of salt, concentration, and climate geography. Alternatively, the use of saline/sodic groundwater for irrigation could affect the soil by altering its physio-chemical properties and structure [113]. Hence, the presence of salinity or sodicity either in soil or groundwater could contaminate each other while, at the same time, could have an equally negative impact on crop growth [114,115].

In semi-arid regions, developments in pumping technologies have exponentially increased groundwater-based irrigation, which has subsequently decreased the salinity caused by waterlogging [116,117]; however, the resulted overdependence has negatively impacted the former. Globally, this trend of increasing groundwater salinity with decreasing water table depth is observed in regions that predominantly use groundwater for irrigation [95,118]. In the Indian state of Punjab and Haryana, the overexploitation of groundwater for irrigation pumping has led to declining groundwater levels and an increasing salt concentration in groundwater [119], while, in Pakistan, using groundwater for irrigation improves the soil and crop yield since it acts as artificial-drainage, which controls waterlogging and water table rise [117].

During dry seasons, the impact of irrigation-induced salinity and sodicity on groundwater can be especially elevated as the water table is generally low; therefore, the extent and concentration of salt contamination could be high [95]. In coastal regions, additional pumping of groundwater to offset the irrigation demand increases the risk of seawater intrusions [38,70]. Repeated irrigation with saline and sodic water leads to the formation of an impermeable layer along the capillary fringe (a layer in which the groundwater seeps up from the water table to fill pores in the overlying region by capillary action) since the pores in the overlying layer becomes occupied with salts [120]. This affects the water cycle by obstructing the interaction between the groundwater table with the sub-surface flows and surface water, reducing the evapotranspiration potential by preventing the saturation of the soil (by groundwater) above the capillary fringe, etc. [121]. Further formation of such layer along the aquifer boundary could affect the aquifer storage properties, for example, by decreasing the specific storage or specific yield of the aquifer [121]. In addition, pumping of saline groundwater, in the long run, could cause the accumulation of salts along the column of the bore well (commonly ~10–25 cm in diameter), which could affect the casing and cause further groundwater contamination (more severe in the case of steel casings since the saline environment acts as a catalyst to corrosion and leads to higher iron content) [70,122].

7. Traditional Strategies for Mitigating High Soil Salinity and Sodicity

The major challenge in the reclamation of soil affected by salinity and sodicity is the removal of salts from the root zone, which is also the most effective way to minimize or completely overcome the detrimental effects of salinity and sodicity [17,123]. Globally, soil reclamation activities are challenging due to lack of awareness, high implementation costs and inaccessibility to well-developed technologies [124]; however, there have been several traditional strategies that are being widely followed to minimize or mitigate soil salinity and sodicity (Table 2).

Table 2. Mitigation options for salinity and sodicity hazard (Adapted from Vargas et al., 2018 [125]).

Category	Types/options	Techniques
Agronomic measures	**Hydro-technical** (a) Irrigation System (b) Drainage Systems	 Sprinkling, drip irrigation, surface and sub-surface irrigation Horizontal and vertical drainage
	Agro-technical (a) Surface regulation (b) Subsurface regulation	 Levelling, Ridging, Furrowing Slitting, Moiling, Deep tilling
	Bio-chemical- Nutrient and manure application, soil acidification, etc.	Overall application, scattering, local, green manure, organic carbon sequestration
	Structural- amend the surface structure mainly in plough layer	Sand and clay application, Ditching, Deep ploughing
Engineering	**Increase storage**	Construct supplemental water storage structures such as dams and reservoirs (e.g., ponds and tanks)
	Improve drainage infrastructure	Develop artificial drainage structures (both surface and sub-surface), bio-drainage (e.g., planting eucalyptus)
	Reduce losses	Improve distribution systems (e.g., reduce canal seepage through the lining, opt for drip or sprinkler irrigation, etc.), reuse the drained water, find alternate discharge methods for the drainage effluent, employ rain water harvesting
Policy	**Regulation measures**	Introduce soil health monitoring, water and power pricing, transferable water entitlements, set limits to groundwater pumping and recharge
	Incentives	Increase the cost of hazardous fertilizers, provide funds to encourage soil reclamation, develop public water supply infrastructure (e.g., canal network) in hotspot regions

Table 2. *Cont.*

Category	Types/options	Techniques
Management	**Optimal operation**	Improve the operation of existing irrigation and drainage systems, manage irrigation logs, adopt innovative technologies, regularly monitor soil and groundwater
	Technology application	Use sensor-based devices (e.g., soil moisture sensors), weather predictions, follow irrigation planning and forecasting
	Maintenance	Desilt the irrigation channels and drainage network

The most common and the best strategy to manage irrigation-induced salinity and sodicity in soils include proper tillage and seedbed preparation before planting, levelling of land to ensure uniform water distribution, cyclic irrigation with fresh and saline water, shifting to organic manures, and implementing soil conservation practices [73,126–128].

Potential mitigation strategies for irrigation-induced salinity in arid and semi-arid climatic areas (also referred to as dryland salinity) includes safely disposing saline groundwater, creating artificial drainage mechanisms, mulching with crop residue, opting for alternate saline-friendly plants such as halophytes and deep-rooted trees (deep-rooted trees utilizes the groundwater and creates bio-drainage), and inducing salinity tolerance through molecular approaches [129,130].

In soils with poor soil drainage and shallow water table depths, artificial drainage structures might be effective; however, this is generally not completely feasible in all geographic regions due to physical constraints and high implementation and maintenance costs [28,131]. In such regions, the usage of synthetic fertilizers (a major contributor to salinity) should be minimized, and the application of organo-mineral fertilizers, organic manures, or chlorine-free (less saline) fertilizers should be preferred. Simple strategies such as the application of fertilizers by mixing them with irrigation water have been suggested to decrease salinity and sodicity, as this practice improves the efficiency of fertilizer usage and increases nutrient availability [132].

As an indirect strategy, salt tolerance of crops can be improved by adding certain nutrients; for example, nitrate, calcium, potassium, and salicylic acids can enhance the salt tolerance of crops, such as pepper, tomato, bean, and a variety of other commonly consumed fruits and vegetables [28,133]. Humic acids and non-essential nutrients, such as silicon, have been shown to reduce the deleterious effect of soil translocation of ions from root to shoot, improve the mineral intake and increase root growth [134,135]. Routine leaching (water applied with irrigation accounting for the drainage below the root zone) can be performed in saline and sodic soils with long-term vegetable cropping [136]. Depending on the type of crops and the extent of the crop's sensitivity to salinity and sodicity of the soil, the frequency of maintenance leaching could vary between two times a week to daily [28,137]. Furthermore, it is important to manage the relationships between the average root-zone salinity, the electrical conductivity of irrigation water, and the leaching fraction under conditions of higher irrigation frequency [138–141].

While the use of chemicals, fertilizers, or conditioners might improve the short-term yield under saline/sodic conditions, these amendments cannot truly reclaim the soil [142]. The most effective mitigation strategies involve a combined hydro-bio-physio-chemical approach [25,143]. Although all of the above methods could be used to mitigate the effects of salinity and sodicity, integrated soil management, i.e., a combination of multiple strategies ranging from the selection of salt-tolerant crops to drainage and irrigation systems, and making operation and maintenance decisions (e.g., fertilizer usage, surface preparation) have been shown to be the most effective strategy [144,145]. Since saline and sodic soils are distributed across a vast range of hydro-physiological conditions, different irrigation regimes, agricultural practices (vary with geographic settings), and socio-economic conditions, the success of even the integrated soil management effort primarily relies on the farmer's ability to adopt the right technique and adapt multiple approaches at a given time [25,146]. In addition to effective management techniques, routine and periodic soil testing might be crucial to maintaining the productivity of the soils affected by irrigation-induced salinity and sodicity hazards [147]. Mitigating the effect of salinity and sodicity hazards requires region-specific studies, educating the farmers about the possible remediation strategies, and providing them with financial and physical resources to implement the mitigation plan.

8. Innovative Solutions to Manage Irrigation-Induced Salinity and Sodicity Crisis

Modern technologies provide many opportunities to overcome the shortcomings and drawbacks in traditional approaches to mitigate soil salinity and sodicity and could play a critical role in managing irrigation-induced salinity and sodicity hazards. Innovative solutions are the management strategies that are economical, eco-friendly, and efficient (in terms of both resource and time) in mitigating the irrigation-induced salinity/sodicity hazards. With the emerging advancements in remote sensing in the past decade, several techniques have been developed to map salinity and sodicity-affected regions (hotspots) and create indices (e.g., salinity index, soil salinity and sodicity index, etc.) using multi-spectral satellite data [148,149]. A recent study in Ethiopia over a sugarcane irrigated farm has successfully managed to model and map spatial variations in salinity using remote sensing and Geographic Information Systems, which demonstrates that it is plausible to study irrigation-induced salinity using modern geospatial techniques [150]. Recently, an innovative leaching solution has been developed to manage salinity and sodicity crisis worldwide, which has successfully managed to transport the salts below the rhizosphere (root zone) by percolating salt through the soil without affecting the crops [151]. This innovative leaching is achieved by applying a low-frequency electromagnetic field through the irrigation water before it is applied to the crops, which enables the crops to absorb the water at the same time and enables the salt to be transported below the root zone [152]. In Uzbekistan, where the problem is pervasive, an innovative study relied on a community-based use of an electromagnetic induction meter (EM) to rapidly assess soil salinity. This approach highlighted the use of an EM device in quantifying soil salinity as well as demonstrated the importance of creating a dialogue in the community to improve the management and reclamation of saline lands more efficiently [153]. A recent study by Nickel (2017) [154] suggests that in highly saline areas, planting of perineal grasses such as alfalfa (11 varieties of which are salt-tolerant) over time can improve/reduce the soil salinity. Under this method, complete reclamation of soil in five to ten years is possible with periodical monitoring and timely management modifications (e.g., planting perennial grass over six years showed declining ECs from 7–10 to 4–8) [154].

A good drainage system is critical for removing saline irrigated water [155,156]. While traditional drainage structures, such as surface canals and sub-surface pipes, are effective, they cannot be successful in all regions due to terrain constraints. Recently, bio-drainage, 'the process of pumping excess soil water by deep-rooted plants', has been highly useful and a good alternative to the traditional drainage systems as 98% of the water is absorbed by the plants [157,158]. Moving from typical agricultural practices to new cropping systems, such as agroforestry (e.g., switching from shallow-rooted annual cropping to planting deep-rooted vegetation), has been proven effective in regions affected with extensive irrigation-induced salinity [159]. The development of multi-stress tolerant crops using modern genetic engineering techniques with salt-tolerant genes would play a major role in achieving high crop yield since the salinity problem is becoming common in many regions of the world with unsustainable irrigation practices [125,160]. However, such bio-engineered crops which are completely salt-tolerant have not been invented yet, and it might take a long time to make them commercially available to farmers [161].

Advancements in understanding the biochemical, physiological, and molecular processes of plant growth will enable the development of novel biochemical techniques to improve salt tolerance in crops. One example of such development is the inoculation of plants with growth-promoting rhizobacteria, which has been successfully documented to increase salt stress tolerance by inducing systemic tolerance [162]. Recent research also draws emphasis on the usage of 'Biochar' (solid carbonaceous residue) as a sustainable ameliorant since it is highly effective in reclaiming physico-chemical and biological properties of salinity and sodicity affected soils [163,164].

9. Conclusions

Salinity and sodicity affect the productivity of irrigated lands and pose one of the major environmental and resource-related challenges facing the world today. Unscientific cultivation practices and soil degradation by salinization and sodification alter the physio-chemical properties of the soil, reduce infiltration rates, increase the surface runoff, and significantly reduce agricultural yield. Salinity and sodicity affect the underlying aquifers through the leaching of salts, contaminating groundwater both locally and regionally. The management of saline and sodic soils requires several resources and strategies, including the usage of non-saline or less saline water for irrigation, development of proper drainage facilities (artificial drainage), inorganic or mineral amendments, the addition of soil ameliorants, and cultivation of salt-tolerant crops. Integrated soil fertility management practices (based on agronomic principles for sustainable agriculture) show promising prospects in mitigating the hazardous effects of salinity and sodicity on soil and groundwater than conventional unsustainable irrigation practices. Modern technological solutions, such as Electromagnetic Induction sensors, can rapidly analyze the extent of in situ salinity, and satellite remote sensing approaches can aid in the large-scale mapping of salinity-affected lands. There is a need for a basic understanding of processes contributing to salinity and sodicity of soils regionally and involve relevant stakeholders, principally the farmers and public institutions (government agencies and research institutions) for the expansion, adoption, and awareness about available technologies for the remediation or reclamation of affected lands. Early realization of symptoms (either visual, physical, biological, chemical, or integrative) of salt-affected soils aid in locating areas where potential fertility issues could occur. Large-scale land reclamation projects and the adoption of sophisticated methods of water application could partially or solely inhibit the risk of salinity hazards. Additionally, its equally important to quantify the ecological, agricultural, and socio-economic impacts of soil degradation due to salinity/sodicity and develop novel technologies to efficiently manage and mitigate the hazardous effects of salinity and sodicity on soil and groundwater for sustaining future food and water sustainability.

Author Contributions: Conceptualization, A.M. and S.R.N.; Writing—original draft, A.M.; Writing—review and editing, S.R.N. and A.M.; Literature review, A.M.; Supervision, S.R.N.; Funding acquisition, N.A.-A. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by Lulea University of Technology, Sweden.

Institutional Review Board Statement: Not Applicable.

Data Availability Statement: Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Acknowledgments: The authors would like to express great appreciation to Yusuf Jameel of the Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, and Jayakesh K of the Department of Civil Engineering, School of Engineering, Amrita Vishwa Vidyapeetham, Coimbatore, for their valuable and constructive suggestions during the development of this review article. We also thank the anonymous reviewers for critically reading the manuscript and suggesting substantial improvements.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bennett, S.J.; Barrett-Lennard, E.G.; Colmer, T.D. Salinity and waterlogging as constraints to saltland pasture production: A review. *Agric. Ecosyst. Environ.* **2009**, *129*, 349–360. [CrossRef]
2. Rengasamy, P. Soil salinization. In *Oxford Research Encyclopedia of Environmental Science*; Oxford University Press: Oxford, UK, 2016. [CrossRef]
3. Shahid, S.A.; Zaman, M.; Heng, L. Soil salinity: Historical perspectives and a world overview of the problem. In *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*; Springer: Cham, Switzerland, 2018; pp. 43–53.
4. Rengasamy, P. World salinization with emphasis on Australia. *J. Exp. Bot.* **2006**, *57*, 1017–1023. [CrossRef]
5. Jordán, M.M.; Navarro-Pedreño, J.; García-Sánchez, E.; Mateu, J.; Juan, P. Spatial dynamics of soil salinity under arid and semi-arid conditions: Geological and environmental implications. *Environ. Geol.* **2004**, *45*, 448–456. [CrossRef]
6. Burger, F.; Čelková, A. Salinity and sodicity hazard in water flow processes in the soil. *Plant Soil Environ.* **2003**, *49*, 314–320. [CrossRef]
7. Rhoades, J.D.; Miyamoto, S. Testing soils for salinity and sodicity. In *Soil Testing and Plant Analysis*; Westerman, R., Ed.; Wiley: Hoboken, NJ, USA, 1990; pp. 299–336.
8. Richards, L.A. *Diagnosis and Improvement of Saline and Alkali Soils*; Agriculture Handbook No. 60; US Department of Agriculture: Washington, DC, USA, 1954.
9. Northcote, K.H.; Srene, J. *Australian Soils with Saline and Sodic Properties*; Soil Publication No. 27; Transport and Road Research Laboratory: Crowthorne, UK, 1972.
10. Scherer, T.F.; Seelig, B.; Franzen, D. *Soil, Water and Plant Characteristics Important to Irrigation*; NRCS Publications: Washington, DC, USA, 1996; p. 14. Available online: https://library.ndsu.edu/ir/bitstream/handle/10365/9480/eb66_1996.pdf?sequence=1 (accessed on 5 October 2021).
11. Alonge, T.; Ojo, O.; Adejumobi, A. Electrical conductivity based classification and mapping of salt affected soils in kampe-omi irrigation scheme. *Glob. Sci. J.* **2019**, *6*, 1075–1085.
12. Odeh, I.O.A.; Onus, A. Spatial analysis of soil salinity and soil structural stability in a semiarid region of New South Wales, Australia. *Environ. Manag.* **2008**, *42*, 265–278. [CrossRef]
13. Shahid, S.A.; Rahman, K. Soil salinity development, classification, assessment and management in irrigated agriculture. In *Handbook of Plant and Crop Stress*; Pessarakli, M., Ed.; CRC Press: Boca Raton, FL, USA, 2010; p. 18.
14. Lin, Z.-Q.; Bañuelos, G.S. Soil salination indicators. In *Environmental Indicators*; Springer: Dordrecht, The Netherlands, 2015; pp. 319–330.
15. Shahid, S.A.; Zaman, M.; Heng, L. Introduction to soil salinity, sodicity and diagnostics techniques. In *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*; Springer: Cham, Switzerland, 2018; pp. 1–42.
16. Waskom, R.M.; Bauder, T.; Davis, J.G.; Andales, A.A. *Diagnosing Saline and Sodic Soil Problems*; Colorado State University Extension Publications: Fort Collins, CO, USA, 2012.
17. Shrivastava, P.; Kumar, R. Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. *Saudi J. Biol. Sci.* **2015**, *22*, 123–131. [CrossRef]
18. Rietz, D.N.; Haynes, R.J. Effects of irrigation-induced salinity and sodicity on soil microbial activity. *Soil Biol. Biochem.* **2003**, *35*, 845–854. [CrossRef]
19. Warrence, N.; Bauder, J.W.; Pearson, K.E. *Basics of Salinity and Sodicity Effects on Soil Physical Properties*; Department of Land Resources and Environmental Sciences, Montanta State University-Bozeman: Bozeman, MT, USA, 2002.
20. Ezlit, Y.D.; Smith, R.J.; Raine, S.R. *A Review of Salinity and Sodicity in Irrigation*; CRC Irrigation Futures Irrigation Matters Series no. 01/10; CRC for Irrigation Futures: Cannon Hill, Australia, 2010; p. 60.
21. Oster, J.D.; Shainberg, I. Soil responses to sodicity and salinity: Challenges and opportunities. *Soil Res.* **2001**, *39*, 1219. [CrossRef]
22. Ondrasek, G.; Rengel, Z.; Veres, S. Soil salinisation and salt stress in crop production. In *Abiotic Stress in Plants—Mechanisms and Adaptations*; IntechOpen: London, UK, 2011; Available online: https://www.intechopen.com/chapters/18402 (accessed on 5 October 2021).
23. Culverwell, T.L.; Swinford, J.M. Attempts at improving irrigation water quality in northern Zululand. In Proceedings of the South African Sugar Technologists Association, Mount Edgecombe, South Africa, 2–6 June 1986; pp. 168–171.
24. Haynes, R.J.; Rietz, D.N. Effect of irrigation-induced salinity and sodicity on sugarcane yields, soil chemical and microbial properties. In Proceedings of the 18th World Congress of Soil Science, Philadelphia, PA, USA, 15 July 2006.
25. Shahid, S.A.; Zaman, M.; Heng, L. Salinity and sodicity adaptation and mitigation options. In *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*; Springer: Cham, Switzerland, 2018; pp. 55–89.
26. Minhas, P.S.; Qadir, M.; Yadav, R.K. Groundwater irrigation induced soil sodification and response options. *Agric. Water Manag.* **2019**, *215*, 74–85. [CrossRef]
27. Yuan, C.; Feng, S.; Wang, J.; Huo, Z.; Ji, Q. Effects of irrigation water salinity on soil salt content distribution, soil physical properties and water use efficiency of maize for seed production in arid Northwest China. *Int. J. Agric. Biol. Eng.* **2018**, *11*, 137–145. [CrossRef]
28. Machado, R.; Serralheiro, R. Soil salinity: Effect on vegetable crop growth. Management practices to prevent and mitigate soil salinization. *Horticulturae* **2017**, *3*, 30. [CrossRef]

29. Thimmappa, K.; Sharma, D.K.; Dagar, J.C.; Raju, R. Reclamation of salt-affected soils: Socioeconomic impact assessment. In *Innovative Saline Agriculture*; Springer: New Delhi, India, 2016; pp. 489–505.
30. Qadir, M.; Quillérou, E.; Nangia, V.; Murtaza, G.; Singh, M.; Thomas, R.J.; Drechsel, P.; Noble, A.D. Economics of salt-induced land degradation and restoration. *Nat. Resour. Forum* **2014**, *38*, 282–295. [CrossRef]
31. Hadrich, J.C. *Managing the Economics of Soil Salinity*; Department of Agribusiness and Applied Economics, Agricultural Experiment Station, North Dakota State University: Fargo, ND, USA, 2011.
32. Naifer, A.; Al-Rawahy, S.A.; Zekri, S. Economic impact of salinity: The case of al-batinah in Oman. *Int. J. Agric. Res.* **2011**, *6*, 134–142. [CrossRef]
33. Madden, B.; Hayes, G.; Duggan, K. *National Investment in Rural Landscapes: An Investment Scenario*; The Virtual Consulting Group & Griffin-nrm Pty Ltd.: Canberra, Australia, 2000.
34. Abrol, I.P.; Yadav, J.S.P.; Massoud, F.I. *Salt-Affected Soils and Their Management*; FAO Soils Bulletin 39; FAO United Nations: Rome, Italy, 1988.
35. Mau, Y.; Porporato, A. A dynamical system approach to soil salinity and sodicity. *Adv. Water Resour.* **2015**, *83*, 68–76. [CrossRef]
36. Daliakopoulos, I.N.; Tsanis, I.K.; Koutroulis, A.; Kourgialas, N.N.; Varouchakis, A.E.; Karatzas, G.P.; Ritsema, C.J. The threat of soil salinity: A European scale review. *Sci. Total Environ.* **2016**, *573*, 727–739. [CrossRef] [PubMed]
37. Hassani, A.; Azapagic, A.; Shokri, N. Predicting long-term dynamics of soil salinity and sodicity on a global scale. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 33017–33027. [CrossRef] [PubMed]
38. Sentís, I.P. Advances in the prognosis of soil sodicity under dryland irrigated conditions. *Int. Soil Water Conserv. Res.* **2014**, *2*, 50–63. [CrossRef]
39. Mahmuduzzaman, M.; Ahmed, Z.U.; Nuruzzaman, A.K.M.; Ahmed, F.R.S. Causes of salinity intrusion in coastal belt of Bangladesh. *Int. J. Plant Res.* **2013**, *4*, 8–13. [CrossRef]
40. Abuelgasim, A.; Ammad, R. Mapping soil salinity in arid and semi-arid regions using Landsat 8 OLI satellite data. *Remote Sens. Appl. Soc. Environ.* **2019**, *13*, 415–425. [CrossRef]
41. Stockle, C.O. Environmental impact of irrigation: A review. In Proceedings of the IV International Congress of Agricultural Engineering, Chillan, Chile, 9–11 May 2001; p. 15.
42. Singh, G. Salinity-related desertification and management strategies: Indian experience. *Land Degrad. Dev.* **2009**, *20*, 367–385. [CrossRef]
43. Comerma, J. Regional assessment of soil changes in Latin America and the Caribbean. In *Status of the World's Soil Resources*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2015; pp. 1–38.
44. Alvarez, C.R.; Taboada, M.A.; Gutierrez Boem, F.H.; Bono, A.; Fernandez, P.L.; Prystupa, P. Topsoil properties as affected by tillage systems in the rolling pampa region of Argentina. *Soil Sci. Soc. Am. J.* **2009**, *73*, 1242–1250. [CrossRef]
45. Wu, J.; Vincent, B.; Yang, J.; Bouarfa, S.; Vidal, A. Remote Sensing monitoring of changes in soil salinity: A case study in inner Mongolia, China. *Sensors* **2008**, *8*, 7035–7049. [CrossRef]
46. Irshad, M.; Inoue, M.; Ashraf, M.; Ahmad, Z. The mitigation challenge of salt affected soils in Pakistan. *J. Food Agric. Environ.* **2007**, *5*, 280–283. [CrossRef]
47. Qadir, M.; Qureshi, A.S.; Cheraghi, S.A.M. Extent and characterisation of salt-affected soils in Iran and strategies for their amelioration and management. *Land Degrad. Dev.* **2008**, *19*, 214–227. [CrossRef]
48. Hamidov, A.; Helming, K.; Balla, D. Impact of agricultural land use in Central Asia: A review. *Agron. Sustain. Dev.* **2016**, *36*, 6. [CrossRef]
49. Du Preez, C.C.; van Huyssteen, C.W. Threats to soil and water resources in South Africa. *Environ. Res.* **2020**, *183*, 109015. [CrossRef] [PubMed]
50. Pankova, E.I. Salt-affected soils of Russia: Solved and unsolved problems. *Eurasian Soil Sci.* **2015**, *48*, 115–127. [CrossRef]
51. Munns, R. Comparative physiology of salt and water stress. *Plant Cell Environ.* **2002**, *25*, 239–250. [CrossRef] [PubMed]
52. Lamond, R.E.; Whitney, D.A. *Management of Saline and Sodic Soils*; Kansas State University: Manhattan, KS, USA, 1992.
53. Nauman, T.W.; Ely, C.P.; Miller, M.P.; Duniway, M.C. Salinity yield modeling of the Upper Colorado River Basin using 30-meter resolution soil maps and random forests. *Water Resour. Res.* **2019**. [CrossRef]
54. Cardon, G.E. Salinity ISSUES in Colorado. *Agron. News* **1998**, *12*, 1–3.
55. Seelig, B.D. *Salinity and Sodicity in North Dakota Soils*; North Dakota State University of Agriculture and Applied Science: Fargo, ND, USA, 2000.
56. Zanchi, C.; Cecchi, S. Soil salinisation in the grosseto plain (Maremma, Italy): An environmental and socio-economic analysis of the impact on the agro-ecosystem. In *Coastal Water Bodies*; Springer: Dordrecht, The Netherlands, 2010; pp. 79–90.
57. Colombani, N.; Mastrocicco, M.; Giambastiani, B.M.S. Predicting salinization trends in a lowland coastal Aquifer: Comacchio (Italy). *Water Resour. Manag.* **2015**, *29*, 603–618. [CrossRef]
58. Harper, R.J.; Dell, B.; Ruprecht, J.K.; Sochacki, S.J.; Smettem, K.R.J. Salinity and the reclamation of salinized lands. In *Soils and Landscape Restoration*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 193–208.
59. Rengasamy, P. Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: An overview. *Aust. J. Exp. Agric.* **2002**, *42*, 351. [CrossRef]
60. Muyen, Z.; Moore, G.A.; Wrigley, R.J. Soil salinity and sodicity effects of wastewater irrigation in South East Australia. *Agric. Water Manag.* **2011**, *99*, 33–41. [CrossRef]

61. Hanjra, M.A.; Blackwell, J.; Carr, G.; Zhang, F.; Jackson, T.M. Wastewater irrigation and environmental health: Implications for water governance and public policy. *Int. J. Hyg. Environ. Health* **2012**, *215*, 255–269. [CrossRef] [PubMed]
62. Mehmood, A.; Aslam Mirza, M.; Aziz Choudhary, M.; Kim, K.-H.; Raza, W.; Raza, N.; Soo Lee, S.; Zhang, M.; Lee, J.-H.; Sarfraz, M. Spatial distribution of heavy metals in crops in a wastewater irrigated zone and health risk assessment. *Environ. Res.* **2019**, *168*, 382–388. [CrossRef]
63. Choudhary, O.P.; Kharche, V.K. Soil salinity and sodicity. In *Soil Science: An Introduction*; Indian Society of Soil Science: New Delhi, India, 2018; pp. 353–384.
64. Floerke, M.; Fink, J.; Malsy, M.; Voelker, J.; Alcamo, J. Implications of salinity pollution hotspots on agricultural production. In Proceedings of the EGU General Assembly Conference Abstracts, EGU Vienna, Austria, 17–22 April 2016.
65. Egamberdieva, D.; Renella, G.; Wirth, S.; Islam, R. Secondary salinity effects on soil microbial biomass. *Biol. Fertil. Soils* **2010**, *46*, 445–449. [CrossRef]
66. Ganjegunte, G.; Clark, J. Causes and management of root-zone salinity and sodicity in the arid west Texas: Field-scale experience. In *Research Developments in Saline Agriculture*; Springer: Singapore, 2019; pp. 307–330.
67. Zaman, M.; Shahid, S.A.; Heng, L. Irrigation systems and zones of salinity development. In *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*; Springer: Cham, Switzerland, 2018; pp. 91–111.
68. Liu, Q.; Hanati, G.; Danierhan, S.; Liu, G.; Zhang, Y.; Zhang, Z. Identifying seasonal accumulation of soil salinity with three-dimensional mapping—A case study in cold and semiarid irrigated fields. *Sustainability* **2020**, *12*, 6645. [CrossRef]
69. Choudhary, O.P.; Grattan, S.R.; Minhas, P.S. Sustainable crop production using saline and sodic irrigation waters. In *Alternative Farming Systems, Biotechnology, Drought Stress and Ecological Fertilisation*; Springer: Dordrecht, The Netherlands, 2011; pp. 293–318.
70. Greene, R.; Timms, W.; Rengasamy, P.; Arshad, M.; Cresswell, R. Soil and aquifer salinization: Toward an integrated approach for salinity management of groundwater. In *Integrated Groundwater Management*; Springer: Cham, Switzerland, 2016; pp. 377–412.
71. Ashraf, M.; Rahmatullah, T.M.; Tahir, M.A. Contribution of shallow water table to salinity/sodicity development under fallow and cropped conditions. *Pakistan J. Agric. Sci.* **2006**, *43*, 7–12.
72. McFarlane, D.J.; George, R.J.; Barrett-Lennard, E.G.; Gilfedder, M. Salinity in dryland agricultural systems: Challenges and opportunities. In *Innovations in Dryland Agriculture*; Springer: Cham, Switzerland, 2016; pp. 521–547.
73. Dunin, F.X. Integrating agroforestry and perennial pastures to mitigate water logging and secondary salinity. *Agric. Water Manag.* **2002**, *53*, 259–270. [CrossRef]
74. Jenkin, J.J. Terrain, groundwater and secondary salinity in Victoria, Australia. *Agric. Water Manag.* **1981**, *4*, 143–171. [CrossRef]
75. Pannell, D.J.; Ewing, M.A. Managing secondary dryland salinity: Options and challenges. *Agric. Water Manag.* **2006**, *80*, 41–56. [CrossRef]
76. McCauley, A.; Jones, C.; Jacobsen, J. *Soil pH and Organic Matter*; Montana State University: Bozeman, MT, USA, 2009.
77. Jensen, T.L. Soil pH and the availability of plant nutrients. *IPNI Plant Nutr. Today* **2010**, *2010*, 2.
78. Edelstein, M.; Plaut, Z.; Ben-Hur, M. Water salinity and sodicity effects on soil structure and hydraulic properties. *Adv. Hortic. Sci.* **2010**, *24*, 154–160.
79. Klopp, H.W.; Daigh, A.L.M. Measured saline and sodic solutions effects on soil saturated hydraulic conductivity, electrical conductivity and sodium adsorption ratio. *Arid Land Res. Manag.* **2020**, *34*, 264–286. [CrossRef]
80. Evelin, H.; Devi, T.S.; Gupta, S.; Kapoor, R. Mitigation of salinity stress in plants by arbuscular mycorrhizal symbiosis: Current understanding and new challenges. *Front. Plant Sci.* **2019**, *10*. [CrossRef] [PubMed]
81. Rengasamy, P. Irrigation water quality and soil structural stability: A perspective with some new insights. *Agronomy* **2018**, *8*, 72. [CrossRef]
82. Rowley, M.C.; Grand, S.; Verrecchia, É.P. Calcium-mediated stabilisation of soil organic carbon. *Biogeochemistry* **2018**, *137*, 27–49. [CrossRef]
83. Levy, G.J.; Shainberg, I. Sodic soils. In *Encyclopedia of Soils in the Environment*; Elsevier: Amsterdam, The Netherlands, 2005; pp. 504–513.
84. Singh, K. Microbial and enzyme activities of saline and sodic soils. *Land Degrad. Dev.* **2016**, *27*, 706–718. [CrossRef]
85. Van der Zee, S.E.A.T.M.; Shah, S.H.H.; Vervoort, R.W. Root zone salinity and sodicity under seasonal rainfall due to feedback of decreasing hydraulic conductivity. *Water Resour. Res.* **2014**, *50*, 9432–9446. [CrossRef]
86. UOC. Effects of Salinity and Sodicity on Physical and Hydraulic Properties. Available online: https://ucanr.edu/sites/Salinity/Salinity_Management/Effect_of_salinity_on_soil_properties/Effects_of_salinity_and_sodicity_on_physical_and_hydraulic_properties/ (accessed on 1 October 2021).
87. Rollins, L. *Advanced Topics in Water Chemistry and Salinity*; WateReuse Foundation: Alexandria, VA, USA; U.S. Environmental Protection Agency: Washington, DC, USA, 2007.
88. Heydari, N.; Gupta, A.D.; Loof, R. Salinity and sodicity influences on infiltration during surge flow irrigation. *Irrig. Sci.* **2001**, *20*, 165–173. [CrossRef]
89. Shainberg, I.; Levy, G.J.; Goldstein, D.; Mamedov, A.I.; Letey, J. Prewetting rate and sodicity effects on the hydraulic conductivity of soils. *Aust. J. Soil Res.* **2001**, *39*, 1279–1291. [CrossRef]
90. Sparks, D.L. *Environmental Soil Chemistry*; Elsevier: Amsterdam, The Netherlands, 2003. [CrossRef]

91. Marchuk, A. *Effect of Cations on Structural Stability of Salt-Affected Soils*; The University of Adelaide: Adelaide, Australia, 2013; Available online: https://hekyll.services.adelaide.edu.au/dspace/bitstream/2440/92048/3/02whole.pdf (accessed on 5 October 2021).
92. Hanson, B.R.; Grattan, S.R.; Fulton, A. *Agricultural Salinity and Drainage*; Division of Agriculture and Natural Resources Publication 3375; University of California: Davis, CA, USA, 1999.
93. ANZECC. *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*; Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand: Canberra, Australia, 2000; p. 103.
94. Basu, S.; Kumar, G.; Chhabra, S.; Prasad, R. Role of soil microbes in biogeochemical cycle for enhancing soil fertility. In *New and Future Developments in Microbial Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 149–157.
95. Yan, N.; Marschner, P.; Cao, W.; Zuo, C.; Qin, W. Influence of salinity and water content on soil microorganisms. *Int. Soil Water Conserv. Res.* **2015**, *3*, 316–323. [CrossRef]
96. De Souza Silva, C.M.M.; Francisconi, E. Effect of salinity on soil microorganisms. In *Soil Health and Land Use Management*; IntechOpen: London, UK, 2012; Available online: https://www.intechopen.com/chapters/25277 (accessed on 5 October 2021).
97. Shi, S.; Tian, L.; Nasir, F.; Bahadur, A.; Batool, A.; Luo, S.; Yang, F.; Wang, Z.; Tian, C. Response of microbial communities and enzyme activities to amendments in saline-alkaline soils. *Appl. Soil Ecol.* **2019**, *135*, 16–24. [CrossRef]
98. Pathak, H.; Rao, D.L.N. Carbon and nitrogen mineralization from added organic matter in saline and alkali soils. *Soil Biol. Biochem.* **1998**, *30*, 695–702. [CrossRef]
99. Rasul, G.; Khan, A.A.; Khan, K.S.; Joergensen, R.G. Immobilization and mineralization of nitrogen in a saline and alkaline soil during microbial use of sugarcane filter cake amended with glucose. *Biol. Fertil. Soils* **2009**, *45*, 289–296. [CrossRef]
100. Elmajdoub, B.; Marschner, P. Salinity reduces the ability of soil microbes to utilise cellulose. *Biol. Fertil. Soils* **2013**, *49*, 379–386. [CrossRef]
101. Badran, R.A. Cellulolytic activity of some cellulose-decomposing fungi in salinized soils. *Acta Mycol.* **2014**, *29*, 245–251. [CrossRef]
102. Yang, C.; Wang, X.; Miao, F.; Li, Z.; Tang, W.; Sun, J. Assessing the effect of soil salinization on soil microbial respiration and diversities under incubation conditions. *Appl. Soil Ecol.* **2020**, *155*, 103671. [CrossRef]
103. Mavi, M.S.; Marschner, P. Impact of salinity on respiration and organic matter dynamics in soils is more closely related to osmotic potential than to electrical conductivity. *Pedosphere* **2017**, *27*, 949–956. [CrossRef]
104. Mavi, M.S.; Marschner, P.; Chittleborough, D.J.; Cox, J.W.; Sanderman, J. Salinity and sodicity affect soil respiration and dissolved organic matter dynamics differentially in soils varying in texture. *Soil Biol. Biochem.* **2012**, *45*, 8–13. [CrossRef]
105. Elmajdoub, B. *Microbial Activity and Biomass in Saline Soils as Affected by Carbon Availability*; The University of Adelaide: Adelaide, Australia, 2014; Available online: https://digital.library.adelaide.edu.au/dspace/bitstream/2440/86830/8/02whole.pdf (accessed on 5 October 2021).
106. Kaur, B.; Gupta, S.R.; Singh, G. Bioamelioration of a sodic soil by silvopastoral systems in northwestern India. *Agrofor. Syst.* **2002**, *54*, 13–20. [CrossRef]
107. Wong, V.N.L.; Greene, R.S.B.; Dalal, R.C.; Murphy, B.W. Soil carbon dynamics in saline and sodic soils: A review. *Soil Use Manag.* **2010**, *26*, 2–11. [CrossRef]
108. Rath, K.M.; Maheshwari, A.; Bengtson, P.; Rousk, J. Comparative toxicities of salts on microbial processes in soil. *Appl. Environ. Microbiol.* **2016**, *82*, 2012–2020. [CrossRef] [PubMed]
109. Torbaghan, M.E.; Lakzian, A.; Astaraei, A.R.; Fotovat, A.; Besharati, H. Salt and alkali stresses reduction in wheat by plant growth promoting haloalkaliphilic bacteria. *J. Soil Sci. Plant Nutr.* **2017**, *17*, 1058–1087. [CrossRef]
110. Moradi, A.; Arezoo, T.; Mehran, H.; Khorsandi, F. Effect of salinity on free living—Diazotroph and total bacterial populations of two saline soils. *Afr. J. Microbiol. Res.* **2011**, *5*, 144–148. [CrossRef]
111. Guangming, L.; Xuechen, Z.; Xiuping, W.; Hongbo, S.; Jingsong, Y.; Xiangping, W. Soil enzymes as indicators of saline soil fertility under various soil amendments. *Agric. Ecosyst. Environ.* **2017**, *237*, 274–279. [CrossRef]
112. De Craats, D.; der Zee, S.E.A.T.M.; Sui, C.; Asten, P.J.A.; Cornelissen, P.; Leijnse, A. Soil sodicity originating from marginal groundwater. *Vadose Zone J.* **2020**, *19*. [CrossRef]
113. Fan, X.; Pedroli, B.; Liu, G.; Liu, Q.; Liu, H.; Shu, L. Soil salinity development in the yellow river delta in relation to groundwater dynamics. *Land Degrad. Dev.* **2012**, *23*, 175–189. [CrossRef]
114. Sun, Y.; Mao, X.; Yang, X.; Tong, L.; Tang, M. Variation of groundwater salinity and its influence on crops in irrigation area of Northwest China. *Trans. Chin. Soc. Agric. Eng.* **2010**, *26*, 103–108. [CrossRef]
115. Rengasamy, P. Soil processes affecting crop production in salt-affected soils. *Funct. Plant Biol.* **2010**, *37*, 613. [CrossRef]
116. Kijne, J.W.; Kuper, M. Salinity and sodicity in Pakistan's Punjab: A threat to sustainability of irrigated agriculture? *Int. J. Water Resour. Dev.* **1995**, *11*, 73–86. [CrossRef]
117. Qureshi, A.S.; McCornick, P.G.; Qadir, M.; Aslam, Z. Managing salinity and waterlogging in the Indus basin of Pakistan. *Agric. Water Manag.* **2008**, *95*, 1–10. [CrossRef]
118. Abliz, A.; Tiyip, T.; Ghulam, A.; Halik, Ü.; Ding, J.; Sawut, M.; Zhang, F.; Nurmemet, I.; Abliz, A. Effects of shallow groundwater table and salinity on soil salt dynamics in the Keriya Oasis, Northwestern China. *Environ. Earth Sci.* **2016**, *75*, 260. [CrossRef]
119. Krishan, G. Groundwater Salinity. *Curr. World Environ.* **2019**, *14*, 186–188. [CrossRef]

120. Franzen, D. *Managing Saline Soils in North. Dakota*; North Dakota State University: Fargo, ND, USA, 2007; Available online: https://www.ndsu.edu/soilhealth/wp-content/uploads/2013/03/Managing-saline-sodic-soils_2003.pdf (accessed on 5 October 2021).
121. Rubin, H. Pollution | Groundwater. In *Encyclopedia of Soils in the Environment*; Elsevier: Amsterdam, The Netherlands, 2005; pp. 271–281.
122. Mukate, S.V.; Panaskar, D.B.; Wagh, V.M.; Baker, S.J. Understanding the influence of industrial and agricultural land uses on groundwater quality in semiarid region of Solapur, India. *Environ. Dev. Sustain.* **2020**, *22*, 3207–3238. [CrossRef]
123. McCauley, A.; Jones, C. *Salinity and Sodicity Management*; Montana State University-Bozeman: Bozeman, MT, USA, 2005; pp. 4481–4482. Available online: https://landresources.montana.edu/swm/documents/Final_Proof_SW2.pdf (accessed on 5 October 2021).
124. Mugwe, J.; Ngetich, F.; Otieno, E.O. Integrated soil fertility management in sub-Saharan Africa: Evolving paradigms toward integration. In *Zero Hunger. Encyclopedia of the UN Sustainable Development Goals*; Springer: Berlin, Germany, 2019; pp. 1–12. [CrossRef]
125. Vargas, R.; Pankova, E.I.; Balyuk, S.A.; Krasilnikov, P.V.; Khasankhanova, G.M. *Handbook for Saline Soil Management*; FAO of United Nations: Rome, Italy, 2018.
126. Rhoades, J.D.; Kandiah, A.; Mashali, A.M. Management principles and practices for safe use of saline water. In *The Use of Saline Waters for Crop Production*; FAO of United Nations: Rome, Italy, 1992.
127. Diacono, M.; Montemurro, F. Effectiveness of organic wastes as fertilizers and amendments in salt-affected soils. *Agriculture* **2015**, *5*, 221–230. [CrossRef]
128. Ding, Z.; Kheir, A.M.S.; Ali, M.G.M.; Ali, O.A.M.; Abdelaal, A.I.N.; Lin, X.; Zhou, Z.; Wang, B.; Liu, B.; He, Z. The integrated effect of salinity, organic amendments, phosphorus fertilizers, and deficit irrigation on soil properties, phosphorus fractionation and wheat productivity. *Sci. Rep.* **2020**, *10*, 2736. [CrossRef]
129. Munns, R.; Goyal, S.S.; Passioura, J. *Salinity Stress and Its Mitigation*; University of California: Davis, CA, USA, 2005.
130. Rengasamy, P.; Chittleborough, D.; Helyar, K. Root-zone constraints and plant-based solutions for dryland salinity. *Plant Soil* **2003**, *257*, 249–260. [CrossRef]
131. Wang, C.; Wu, J.; Zeng, W.; Zhu, Y.; Huang, J. Five-year experimental study on effectiveness and sustainability of a dry drainage system for controlling soil salinity. *Water* **2019**, *11*, 111. [CrossRef]
132. Çetin, Ö.; Akalp, E. Efficient use of water and fertilizers in irrigated agriculture: Drip irrigation and fertigation. *Acta Hortic. Regiotect.* **2019**, *22*, 97–102. [CrossRef]
133. Shahbaz, M.; Ashraf, M.; Al-Qurainy, F.; Harris, P.J.C. Salt tolerance in selected vegetable crops. *CRC Crit. Rev. Plant Sci.* **2012**, *31*, 303–320. [CrossRef]
134. Gunes, A.; Inal, A.; Bagci, E.G.; Coban, S.; Sahin, O. Silicon increases boron tolerance and reduces oxidative damage of wheat grown in soil with excess boron. *Biol. Plant* **2007**, *51*, 571–574. [CrossRef]
135. Ouni, Y.; Ghnaya, T.; Montemurro, F.; Abdelly, C.; Lakhdar, A. The role of humic substances in mitigating the harmful effects of soil salinity and improve plant productivity. *Int. J. Plant Prod.* **2014**, *8*, 353–374. [CrossRef]
136. Letey, J.; Hoffman, G.J.; Hopmans, J.W.; Grattan, S.R.; Suarez, D.; Corwin, D.L.; Oster, J.D.; Wu, L.; Amrhein, C. Evaluation of soil salinity leaching requirement guidelines. *Agric. Water Manag.* **2011**, *98*, 502–506. [CrossRef]
137. Corwin, D.L.; Rhoades, J.D.; Šimůnek, J. Leaching requirement for soil salinity control: Steady-state versus transient models. *Agric. Water Manag.* **2007**, *90*, 165–180. [CrossRef]
138. Rhoades, J.D. Leaching requirement for exchangeable-sodium control. *Soil Sci. Soc. Am. J.* **1968**, *32*, 652–656. [CrossRef]
139. Rhoades, J.D.; Oster, J.D.; Ingvalson, R.D.; Tucker, J.M.; Clark, M. Minimizing the salt burdens of irrigation drainage waters. *J. Environ. Qual.* **1974**, *3*, 311–316. [CrossRef]
140. Rhoades, J.D. Reclamation and management of salt affected soil after drainage. In Proceedings of the 1st Annual Western Provincial Conference Rationalization of Water and Soil Research and Management, Lightbridge, Canada, 1982.
141. Van Schilfgaarde, J.; Rhoades, J.D. *Water Quality in Relation to Irrigated Agriculture*; U.S. Salinity Laboratory (USDA): Riverside, CA, USA, 1982.
142. Bauder, T.A.; Davis, J.G.; Waskom, R.M. *Managing Saline Soils*; Colorado State University Extension Publications: Fort Collins, CO, USA, 2004.
143. Alcívar, M.; Zurita-Silva, A.; Sandoval, M.; Muñoz, C.; Schoebitz, M. Reclamation of saline-sodic soils with combined amendments: Impact on quinoa performance and biological soil quality. *Sustainability* **2018**, *10*, 3083. [CrossRef]
144. Maqsood, M.A.; Hussain, S.; Aziz, T.; Ashraf, M. Sustainable agriculture through integrated soil fertility management on degraded lands. In *Developments in Soil Salinity Assessment and Reclamation*; Springer: Dordrecht, The Netherlands, 2013; pp. 759–768.
145. Yadav, S.K.; Soni, R. Integrated soil fertility management. In *Soil Fertility Management for Sustainable Development*; Springer: Singapore, 2019; pp. 71–80.
146. Shahid, S.A.; Al-Shankiti, A. Sustainable food production in marginal lands—Case of GDLA member countries. *Int. Soil Water Conserv. Res.* **2013**, *1*, 24–38. [CrossRef]
147. Fipps, G. *Irrigation Water Quality Standards and Salinity Management Strategies*; The Texas A&M University System Extension Publications: College Station, TX, USA, 2003.
148. Dehni, A.; Lounis, M. Remote sensing techniques for salt affected soil mapping: Application to the Oran region of Algeria. *Procedia Eng.* **2012**, *33*, 188–198. [CrossRef]

149. Singh, R.P.; Setia, R.; Verma, V.K.; Arora, S.; Kumar, P.; Pateriya, B. Satellite remote sensing of salt-affected soils: Potential and limitations. *J. Soil Water Conserv.* **2017**, *16*, 97. [CrossRef]
150. Asfaw, E.; Suryabhagavan, K.V.; Argaw, M. Soil salinity modeling and mapping using remote sensing and GIS: The case of Wonji sugar cane irrigation farm, Ethiopia. *J. Saudi Soc. Agric. Sci.* **2018**, *17*, 250–258. [CrossRef]
151. AQUA4D An Innovative Sustainable Solution to Soil Salinity. Available online: https://aqua4d.com/an-innovative-sustainable-solution-to-soil-salinity/ (accessed on 31 January 2021).
152. Cahn, M.; Bali, K. *Drought Tip: Managing Salts by Leaching*; University of California: Los Angeles, CA, USA, 2015. [CrossRef]
153. Akramkhanov, A.; Ul Hassan, M.; Hornidge, A.-K. Redrawing soil salinity innovation-focused stakeholder interaction for sustainable land management in Khorezm Province, Uzbekistan. *Water* **2018**, *10*, 208. [CrossRef]
154. Nickel, R. New Life for Saline Soil. Available online: https://www.agriculture.com/crops/cover-crops/new-life-for-saline-soil (accessed on 31 January 2021).
155. Christen, E.W.; Ayars, J.E. *Subsurface Drainage System Design and Management in Irrigated Agriculture: Best Management Practices for Reducing Drainage Volume and Salt Load*; CSIRO Land and Water: Griffith, Australia, 2001.
156. Christen, E.; Ayars, J.; Hornbuckle, J. Subsurface drainage design and management in irrigated areas of Australia. *Irrig. Sci.* **2001**, *21*, 35–43. [CrossRef]
157. Akram, S.; Kashkouli, H.A.; Pazira, E. Sensitive variables controlling salinity and water table in a bio-drainage system. *Irrig. Drain. Syst.* **2008**, *22*, 271–285. [CrossRef]
158. Kapoor, A.S. Bio-drainage: Potential and limitations. In Proceedings of the 9th International Drainage Workshop, Utrecht, The Netherlands, 10–13 September 2003.
159. George, S.J.; Harper, R.J.; Hobbs, R.J.; Tibbett, M. A sustainable agricultural landscape for Australia: A review of interlacing carbon sequestration, biodiversity and salinity management in agroforestry systems. *Agric. Ecosyst. Environ.* **2012**, *163*, 28–36. [CrossRef]
160. Yamaguchi, T.; Blumwald, E. Developing salt-tolerant crop plants: Challenges and opportunities. *Trends Plant Sci.* **2005**, *10*, 615–620. [CrossRef]
161. Fita, A.; Rodríguez-Burruezo, A.; Boscaiu, M.; Prohens, J.; Vicente, O. Breeding and domesticating crops adapted to drought and salinity: A new paradigm for increasing food production. *Front. Plant Sci.* **2015**, *6*. [CrossRef]
162. Kaushal, M.; Wani, S.P. Rhizobacterial-plant interactions: Strategies ensuring plant growth promotion under drought and salinity stress. *Agric. Ecosyst. Environ.* **2016**, *231*, 68–78. [CrossRef]
163. Saifullah; Dahlawi, S.; Naeem, A.; Rengel, Z.; Naidu, R. Biochar application for the remediation of salt-affected soils: Challenges and opportunities. *Sci. Total Environ.* **2018**, *625*, 320–335. [CrossRef] [PubMed]
164. Amini, S.; Ghadiri, H.; Chen, C.; Marschner, P. Salt-affected soils, reclamation, carbon dynamics, and biochar: A review. *J. Soils Sediments* **2016**, *16*, 939–953. [CrossRef]