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REVIEW ARTICLE

Sustainable management of saline and sodic soils for growing vegetable crops - A review

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Abstract

Vegetables are essential that play a crucial role in human nutrition. Salinity is a major constraint affecting agricultural productivity globally. Salt affects soils comprise approximately 20 % of cultivated land and 33 % of irrigated land. Salt stress hampers plant growth, thereby reducing the yield and quality of various crops. Salinity and sodicity adversely affect the biological, physical and chemical properties of soil, leading to reduced productivity and land degradation, particularly in irrigated and rainfed agricultural systems. Salinity reduces protein, fatty acid and total carbohydrate content in crops, while often increasing the accumulation of amino acids. The presence of soluble salts and excess sodium ions (Na^+) in soil adversely affects plant health, emphasizing the need for effective resource management and sustainable practices. High salinity leads to surface crusting, reduced water infiltration, sodium-induced soil dispersion and decreased hydraulic conductivity (HC), all of which negatively impact plant development. Sodicity refers to the presence of excessive exchangeable sodium in soil relative to calcium and magnesium, which disrupts soil structure and fertility. High sodicity inhibits plant growth due to salt toxicity, nutritional imbalances and reduced availability of essential minerals in the soil. This review discusses the impact of saline and sodic soils on various vegetable crops and explores sustainable management practices to mitigate their effects.

Keywords: management practices; saline soil; sodic soil; vegetable crops

Introduction

Vegetables are essential for small-scale farmers because they yield much higher returns per hectare than traditional staple crops (1). Compared to staple crops, vegetables are believed to be more susceptible to adverse climatic conditions such as drought, high or low temperatures, salt, waterlogging, an excess or deficiency of mineral nutrients and variations in soil pH (2). High levels of soluble salts in the soil limit the production of most crops, including vegetables, in many areas of the world particularly in arid and semi-arid regions such as parts of South Asia (e.g., India and Pakistan), the Middle East (e.g., Iran, Iraq and Saudi Arabia), North Africa (e.g., Egypt and Algeria), Central Asia (e.g., Uzbekistan and Turkmenistan) and parts of Australia and southwestern United States. Climate change is expected to exacerbate these environmental issues by increasing evapotranspiration and reducing freshwater availability in these vulnerable regions (3). Significant crop-to-crop diversity in vegetable crop salt tolerance has been noted, much like with other crops (4). While crops such as broccoli, cauliflower, tomato, eggplant, potato, turnip, radish, lettuce, pumpkin, cucumber and pepper exhibit moderate sensitivity, red beet (*Beta vulgaris*) is relatively salt-tolerant. In contrast, carrots, onions, peas and okra are highly susceptible to salinity (Table 1 and 2).

This term “salinity” is derived from the Latin words “salinium,” meaning “position or quality of being,” and “salt cellar.” “Salt” is the term use to describe the dissolved salt found in soil or water. Soil salinity is a significant issue that threatens agricultural plants and restricts worldwide agriculture, especially on irrigated farmlands, in areas where high-salt groundwater is used for irrigation (5). Plants that are salt tolerant, or resistant to their natural strength, may withstand the damaging effects of excessive salt on their roots or leaves

Table 1. Threshold level of salinity for vegetable crops

Vegetable	Threshold levels (dS m^{-1})	Reference
Pea (*Pisum sativum* L.)	1.5	(55)
Potato (*Solanum tuberosum*)	1.7	(56)
Cauliflower (*Brassica oleracea var. Botrytis*)	1.8	(55)
Sweet pepper (*Capsicum annuum*)	1.5	(56)
Broccoli (*Brassica oleracea var. Italic*)	1.8	(56, 57)
Carrot (*Daucus carota*)	1.0	(56, 57)
Bhendi (*Abelmoschus esculentus L.*)	1.2	(55)
Brinjal (*Solanum melongena*)	1.1	(56)
Tomato (*Solanum lycopersicum*)	2.5	(56)

Table 2. Categorization of vegetable cultivars based on salinity tolerance

Moderately sensible (0-4 mS/cm)	Sensible (4-6 mS/cm)	Tolerant (6-8 mS/cm)	Highly tolerant (8-12 mS/cm)	Reference
Carrot Cucumber Watermelon Beans Radish	Onion Lettuce Melon Potato Pumpkin	Cabbage Tomato Spinach	Asparagus Beetroot	(21, 84, 85)

without experiencing any severe adverse effects (6).

Approximately 25 % of the world's irrigated land equivalent to 45 million hectares is affected by salinity, compromising nearly one-third of global food production (7). Global agriculture, particularly in irrigated places, is hampered by soil salinity, another significant issue in locations where irrigation uses high ground salt water (5). The profitability of many horticultural harvests, especially extremely soft vegetables at the plant's entry, is reduced by excessive soil salt. Symptoms of salt stress in susceptible plants might include decreased growth, turgor loss, leaf shrinkage, folding and epinasty, leaf removal, decreased photosynthesis, respiratory abnormalities, loss of cellular integrity, tissue necrosis and plant death (8, 9).

If the extract saturation (ECE) electrical conductivity in the root zone is greater than 4 dS m^{-1} (around 40 mM Nacl) at 25 dC and includes 15 % exchangeable sodium, the soil is considered salty (Table 3). The yield of most agricultural plants decreases with ECE, even if the bulk of crops exhibit a dip in productivity at lower ECs (10, 11). Globally, soil erosion and decreased agricultural productivity are caused by soil salinization (12). Most vegetable crops are natively glycophytes, making salt stress one of the most severe environmental conditions that limits their growth.

Approximately one-third of the world's irrigated land is affected by salinity (13), posing a significant threat to agricultural productivity. Alongside other environmental factors such as high winds, elevated temperatures, drought and floods, soil salinity is among the most damaging, especially in uncultivated areas, where it severely reduces crop yield and quality (14, 15). Additionally, poor soil structure and inadequate aeration further limit plant growth and productivity (16).

Soil salinity is a major issue in irrigated agriculture. Saline soils are common in hot, arid parts of the world with little potential for agriculture. Since, most crops grown in these places are irrigated, 20 % of irrigated land globally suffers from secondary salinization, which is exacerbated by inadequate irrigation (17). Salinity is the result of soil salts building up when rainfall is insufficient to eliminate ions from the soil profile (18).

Excessive gypsum treatment has been demonstrated to reduce electrical conductivity and the sodium adsorption ratio (SAR) while increasing the removal of excess Na^+ from soil. Gypsum is a common agricultural soil additive used for sodic soil reclamation because of its high solubility, ease of application and low cost, helping to mitigate the negative effects of high salt concentrations in irrigation water.

Salt naturally exists in soil, surface water and groundwater. The most common salt is sodium chloride, though other salts like magnesium, calcium and potassium may also be present. While soluble salts may have less sodic acid, they often contain high levels of sodium. Sodic soils, characterized by high levels of exchangeable sodium, are unsuitable for most crops as they elevate soil pH (typically 8.5 -12), disrupt soil structure and impair water infiltration and aeration (Table 3). This disrupts the soil's chemical balance and structure. As a result, the soil cannot easily absorb air, rain, or irrigation water. It becomes sticky when wet and forms hard crusts when dry. This problem usually doesn't occur in sandy soils, as they lack enough clay to develop such issues (19). This review focuses on the cultivation of various vegetable crops under saline and sodic soil conditions and discusses effective management strategies to enhance productivity in such challenging environments (Table 4).

Table 3. Characteristics of salt affected soil

Different Salt Classes Affecting Soils	Electrical conductivity (ECe) at 25 C (dS m^{-1})	Exchange Sodium percentage (ESP)	Sodium adsorption ratio (SAR)	Reaction (pH value)	Reference
Saline soil	>4	<15	< 13	<8.5	(54)
Sodic (alkali) soil	<4	>15	>13	>8.5-10	

Table 4. Management of salinity

Techniques of management	Utilizing vegetables	Reference
Lowering of the groundwater	Groundwater withdrawal from rivers can lower coastal areas' groundwater levels, allow seawater intrusion and hinder crop cultivation. Reducing salt leaching is necessary to lessen the consequences of salinity and lowering the water table and ensuring adequate drainage are crucial to avoiding salt buildup	(66)
Building of structures for water harvesting	To mitigate salinity impacts, groundwater use must be substituted by freshwater irrigation. Proper rainwater harvesting structures, such as floodwater harvesting, macro-catchments and micro-catchment, are needed to sustain agricultural livelihoods in drylands, including spat irrigation and runoff farming	(67)
Restoration of salinized soils	Soil reclamation is a method that extracts soluble salts from crop roots, reducing salinity impact through practices like leaching, improved water management, surface and subsurface drainage, organic fertilizers and salt-tolerant cultivars	(6, 68, 69)
Leaching of salt	The leaching process for bell peppers increases with the salt of the irrigation water	(70)
Systems of surface and subsurface drainage	Drainage is the act of eliminating surface or subsurface water using artificial or natural systems, which lowers the water table and lessens the possibility of salt buildup and a rising groundwater table	(71)
Organic or chemical fertilizers	By lowering Na^+ toxicity, boosting water-holding capacity and releasing vital minerals, organic fertilizers enhance soil health. Potash fertilizers improve soil salinity, increase crop production and aid in element uptake. Nitrogen fertilizers overcome boron toxicity and improve soil's Cl^- toxicity effects	(72, 73)
Mulching the soil	Swiss chard-Mulching using rice straw and stones to increase crop yield	(74)
Calcium	Sweet Pepper and tomato improve fruit quality and output while reducing blossom end rot	(75)
Phosphorus	Salinity sensitivity was reduced by up to 3.5 dS m^{-1} by radish	(76)
Sulfur	*Brassica* spp. and legume crops: enhanced salinity stress and defensive mechanisms	(77)
Relative humidity	The cultivation of melons under salt stress fared better at 70 % relative humidity than at 30 %	(78)
Grafting to tolerant rootstock	Melon and pumpkin rootstock combinations: Melon rootstocks almost eliminate Na, whilst pumpkin rootstocks exclude 74 % of accessible Na	(79)
Seed priming	Melons treated with 18 dS m^{-1} NaCl solution had less adverse effects than those of salty irrigation	(80)
Foliar application of nutrient	Brinjal-$K_2{\cdot}HPO_4$ increased fruit yield	(81)
Elevated CO_2 concentration	Tomato-increasing aerial CO_2 concentration, alleviate the negative salinity effects	(82)
Irrigation methods	Sprinkler irrigation reduces salt leaching by releasing little quantities of water for infiltration, making it perfect for regions that are often watered Drip irrigation is a highly effective method for saline-irrigated lands, as it maintains low salt levels in the plant root zone	(6)
Crop rotation	Crop rotation, a strategy to combat salinity, commonly uses cultivars that are tolerant of both water and salt Long-fallowing crops, however, may cause groundwater levels to rise, which would impede agricultural development. According to studies, annual and perennial crops should be cultivated alternately	(83)

Saline soil

Saline soils are defined by the presence of excess soluble salts, which can hinder the growth and yield of most agricultural crops, even at electrical conductivity of the extract (ECe) levels below standard thresholds (11). This ECe leads to reduced yields for most agricultural plants. Saline soils are well-structured nature, saline soils are not sodic and contain enough soluble salts to negatively impact the development of most agricultural plants (20). Salt types and concentrations are the primary determinants of the chemical properties of soils that are classified as saline. It is the quantity of soluble salts that determines the soil solution's osmotic pressure. Magnesium and calcium concentrations on the exchange complex and in the soil solution might differ significantly. The chemical composition of saline soils varies depending on the dominant salts, with sodium chloride being the most common. However, magnesium, calcium and occasionally potassium both in soluble and exchangeable forms also contribute significantly to the ionic profile (21). Saline soils are widespread in hot, arid regions and generally have limited agricultural potential. Secondary salinization, which affects about 20 % of the world's irrigated land, results primarily from poor irrigation management and is a major constraint to crop production in these areas (17). Human activities, especially irrigated agriculture in arid and semi-arid zones, accelerate secondary salinization by causing salt accumulation in soils and water sources. Additionally, natural processes such as mineral weathering contribute to the gradual buildup of salts. When minerals weather, they release salts, which are composed of electrically charged atoms or molecules called ions, into the soil. Secondary salinization, which affects 20 % of irrigated land worldwide and is made worse by inadequate irrigation management, is cited as the primary crop harming most crops farmed in these countries. Irrigated agriculture, a common human activity in arid and semi-arid regions, causes secondary salinization of the soil and water sources. Because saline soil is typically found in hot, arid regions of the world, they offer limited promise for agriculture (17). Electrically charged atoms or molecules known as ions make up salts, which are found in soil. Weathering minerals releases ions into the soil. Irrigation and fertilization are possible because they move upstream from shallow groundwater to land. Salts build up when the soil profile isn't sufficiently cleared of ions by rainfall (18).

Impact of salinity stress on the plants

Salinity has a complicated effect on plants and can cause ion toxicity, osmotic stress, imbalances in hormones, nutrient uptake and antioxidant activity. The first physiological reaction to salt stress is a reduction in stomatal closure and leaf elongation (22, 23). Excessive accumulation of sodium (Na^+) and chloride (Cl^-) ions in the lower leaves disrupts the ionic balance, leading to a decline in nutrient absorption and reduced leaf area index ultimately hindering plant development.

In sodic soils, the high osmotic pressure causes plant cells to lose more water than they can absorb, inducing water stress (24, 25). A scarcity of water results in a series of physical, signaling, gene expression, metabolic and physiological processes and activities that eventually limit photosynthesis, biomass accumulation, the leaf area index and yield (26, 27). The primary cause raising the concentration of Na^+ and Cl^- ions and producing plant toxicity in sodic soils is the fact that 50-80% of the soluble salts are NaCl. These ions significantly impact the photosynthetic signaling system or the chemical process behind enzyme function (28, 30).

Sodium ions in saline soils interfere with potassium uptake due to similarities in ionic radii and transport mechanisms. This competitive inhibition often results in potassium (K^+) deficiency in plant tissues, especially in leaves, where K^+ plays a vital role in stomatal regulation, turgor maintenance and overall photosynthetic efficiency (31-33). Salt tension has a significant impact on the intricate plant-physiological and biochemical process of photosynthesis in vegetables (20, 34). In plants that are susceptible to salt, stomata closure may result in a reduction in the efficiency of carboxylation and photosynthesis. Additionally, the over expression of pheophorbide and oxygenase causes chlorophyll to degrade, which impacts photosynthesis (20). Additionally, salt can cause anomalies in the oxygen-evolving complex, cyclic electron transport and PSII activity (35, 36). In lettuce, onions and tomatoes, it was demonstrated that salinity stress reduced stomatal conductance and transpiration rates, deteriorated pigments and light-harvesting complexes and hence reduced the quantum yield of photosynthetic energy and energy dissipation through non-photochemical means.

The secondary effect of salinity on plant cells is the accumulation of dangerous reactive oxygen species (ROS), which change gene expression and cause DNA methylation, regardless of the primary effects of salt stress (37, 38). Furthermore, ROS can cause lipid peroxidation, which raises the membrane's permeability and fluidity (40). In response, plants activate a complex defense system involving both enzymatic (e.g., superoxide dismutase, catalase) and non-enzymatic (e.g., ascorbate, glutathione) antioxidants to mitigate ROS-induced damage (30, 40) (Table 5).

Changes in soil salinity and sodicity

In arid and semiarid environments, irrigation (irrigation agriculture) is the main cause of soil salinity, an issue that is becoming more common in crop production globally. Salinity has an impact on almost one-third of all irrigated land on Earth. When evapotranspiration exceeds precipitation and drainage is inadequate, salts accumulate at the soil surface. A high salt content in the soil profile is a characteristic of saline soils. A range of ion species with varying compositions are frequently present in amounts that impact crop growth (Na^+, Cl^-, HCO_3^-, PO_4^{3-},Ca^{2+}, Mg^{2+}, SO_4^{2-} and borate) (41).

Soil quality is influenced by land use and soil management practices and it differs regionally from field to greater area size (42). Management practices and land use have an impact on the extent and direction of soil changes. It may be beneficial to use and manage land appropriately to enhance soil properties, reduce soil degradation and eventually attain agricultural sustainability (43). Understanding the spatial variability of soil quality and the factors influencing it is essential for planning sustainable land use and improving long-term agricultural productivity (44).

Primary salinization

This happens naturally and is caused by salts collecting because the parent material or groundwater has a lot of salts (3). Salts are naturally formed in both dry and moist sections of the earth (45). Salt-affected soils (SAS) can develop due to high salt levels in the soil, a shallow groundwater table, or the use of saline water for irrigation (46). A major environmental problem that affects natural farming ecosystems worldwide is salinity during drought (47, 48).

Secondary salinization

Secondary salinization results from human-induced activities such as poor drainage, improper fertilizer application, inefficient irrigation systems and the use of salt-laden water for irrigation. Population increases and socioeconomic conditions are the main sources of these problems (3). As there is insufficient drainage, salts that were once evenly dispersed throughout the soil profile are carried to the upper layers by irrigation water and then left behind as the water evaporates. Secondary salinization caused by soil mineral weathering, fertilizer use, immobilized salts already precipitated in soils, atmospheric salt depositions, such as in coastal areas, water logging and excessive irrigation water salinity are the main causes of excessive salt accumulation in soil surface horizons (49).

Mechanism of salinity tolerance

Salinity tolerance in plants involves a complex interplay of

Table 5. Enhancement of possible vegetable crops' resistance to salt through several methods

Vegetable crop	Method used to increase resistance to salt	Characteristics for improved	Reference
Tomato	Application of salicylic acid, thiazuron and amino acids exogenously	Enhanced dry biomass	(60, 66)
Brinjal	Using a foliar spray to apply glycinebetaine (GB) exogenously	Greater yield and growth	(59)
Potato	Applying salts like NaCl and $CaCl_2$ to potato tubers before they are harvested	The shoots' higher dry weight	(62)
Okra	K and humic acid application in a saline media	Increased dry biomass	(58)
Pea	application of methyl jasmonate (Me-JA) to seeds prior to sowing	Higher concentration of proline	(63)
Cauliflower	Adding nitrogen to the growing medium	Higher yield	(64)
Broccoli	Topically applying urea or methyl-jasmonate (MeJA)	Improved growth	(65)

morphological, biochemical, molecular and physiological mechanisms that influence growth and yield (50) (Fig 1). Reducing water loss from stomata and cuticles and increasing water intake by roots promote osmotic adjustment and support morphological and physiological adaptation for resistance to salt-induced osmotic stress (51). A number of molecular networks regulate tolerance and adaptation to salt stress. These networks initiate response mechanisms such as stress protein synthesis, antioxidant overexpression and the accumulation of appropriate solutes to stabilize cells, repair damaged membranes and protect proteins (25, 52).

Based on their response to salt, plants are classified into halophytes and glycophytes. Halophytes thrive and complete their life cycles in saline environments, whereas glycophytes are generally salt-sensitive (53). Plants use two primary strategies to combat salt stress: tissue tolerance and salt avoidance. Ion compartmentalization is also carried out by plants in their tissues. To control their osmotic pressure and preserve the integrity of their metabolic processes, plants continuously produce water-soluble, low molecular weight compatible solutes including proline, glycine betaine and sugars. Plants produce a range of enzymatic and non-enzymatic antioxidants to address the detrimental effects of salt. To protect the cytoplasm of the plant cell from ion toxicity and water stress, ion compartmentalization in the vacuole creates a constant salt concentration in the cytosol during plant tissue tolerance (2).

Effect of salinity and crop reaction in vegetable crops

Bhendi (*Abelmoschus esculentus L.)*

Effect of salinity and crop reaction: Bhendi (*Abelmoschus esculentus* L.) is considered a moderately salt-tolerant crop. Salinity stress affects bhendi, a crop that is semi-tolerant. It can prevent seed germination and lower cotyledon activity of Na^+, sugar and phenol. Fresh pod yield, shoot length and shoot and root weights are all greatly decreased by the salinity of the rooting media. In reaction to salt stress caused by NaCl, ion absorption and ratios are also impacted, with higher concentrations of Na^+ and Cl^- and lower concentrations of K^+ and Ca^{2+}.

Strategies for improving salinity tolerance: Research on enhancing salinity tolerance in okra remains limited (58). Incorporating K and humic acid into a saline medium has been shown to significantly increase okra's tolerance to salt, especially during the seedling stage (Table 5).

Brinjal (*Solanum melongena L.*)

Effect of salinity and crop reaction: In eggplant (*Solanum melongena* L.), salinity stress moderately affects physiological functions, including internal CO_2 concentration, shoot and root biomass and gas exchange parameters, while water use efficiency remains largely unaffected (59). Fruit weight and quantity per plant are greatly reduced by salinity.

Strategies for improving salinity tolerance: There aren't many ways to combat the losses in eggplant production caused by salt in saline environments, however exogenous application of inorganic fertilizers, suitable solutes and bacterial plant growth promotion have been discovered to be effective methods (59). It has been discovered that the detrimental effects of NaCl on plant development, fruit output and total soluble sugar levels can be lessened by applying di-potassium hydrogen orthophosphate ($K_2 \cdot HPO_4$) topically.

Potato (*Solanum tuberosum L.*)

Effect of salinity and crop reaction: Salinity stress significantly impairs the growth and productivity of potato (*Solanum tuberosum* L.), particularly in salt-sensitive cultivars. It adversely affects seedling biomass accumulation, reduces shoot and root lengths and alters molecular responses involved in stress signaling and metabolism. The resulting physiological imbalances, such as ion toxicity and osmotic stress, lead to reduced tuber yield and quality.

Strategies for improving salinity tolerance: To enhance salt tolerance in potatoes, several strategies have been employed, including the application of exogenous nutrients, 5-aminolevulinic acid (ALA) and genetic engineering. Pre-treatment with NaCl and $CaCl_2$ has shown effectiveness in preparing plants for salt stress, while potassium supplementation in the rooting medium helps mitigate salinity effects, particularly under potassium-deficient conditions. However, excessive potassium application beyond the recommended threshold does not confer additional benefits.

Salt-tolerant cultivars

The accumulation of salts in soil is a widespread issue that negatively influences plant physiological processes and

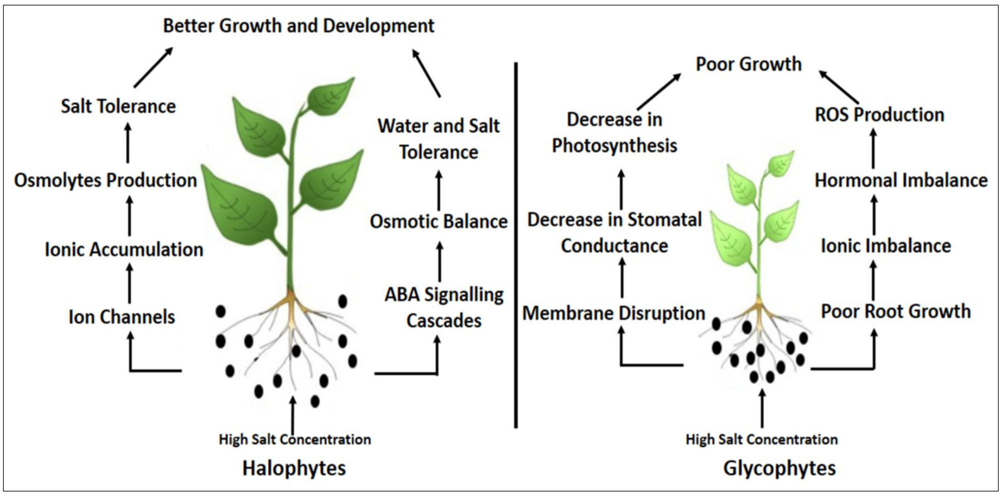

Fig. 1. Stress signaling, osmotic adjustment, enzyme activity, polyamines and ionic compartmentalization all regulate the physiological and metabolic processes of halophytes.

reduces crop yields. The development and cultivation of salt-tolerant potato cultivars represent a critical strategy for mitigating these effects.

Sodicity

Sodic soils are those that have so much exchangeable salt in their exchange complex that it hinders the growth of most agricultural plants. A non-saline soil that has enough exchangeable sodium to negatively impact crop yield and soil physical characteristics by altering soil structure is often referred to as a sodic soil (20). Poorly structured soils with colloidal clays scattered over the uppermost layer are known as sodic soils. Some of these soils' characteristics include poor aeration, crusting of the surface soil, low permeability and infiltration rates, difficulty tilling and difficulty permitting plant roots to penetrate.

Sodic soils typically have a high pH (above 8.5) due to the absence of calcium carbonate buffering and the alkaline hydrolysis of sodium salts (86, 87). High sodicity inhibits plant development due to a lack of mineral nutrients in the soil, a plant nutritional imbalance and Na toxicity. Sodicity refers to the ratios of transferable sodium to calcium and magnesium in soil (88). Sodic conditions develop when sodium ions preferentially bind to negatively charged sites on soil colloids, displacing calcium and magnesium and causing clay dispersion (89). Sodic soils are the most common problem in the world's irrigated desert and semi-arid regions. Furthermore, the presence of bicarbonates, soluble sodium carbonates and interchangeable sodium in irrigation water adversely affects the increasing salinity/alkalinity in the agricultural soils in these regions (90). Crop type, variety, developmental stage, soil texture, salt type and quantity, cultural techniques and climate (temperature, relative humidity and rainfall) all affect how severe the negative effects (91, 92). Sodic soils inhibited asparagus and tomato development more than saline soils did, indicating that both plants are vulnerable to sodicity, as shown by the sensitivity of specific varieties listed in Table 6. Similarly, the bean demonstrated a strong sensitivity to sodicity by failing to survive under such conditions (93).

The impacts of sodicity

- Decreased water movement through the soil, which inhibits leaching and might eventually lead to the buildup of salt and the production of salt water.
- Increasing corrosion and spreading throughout the subsurface, which may result in the formation of lanes and tunnels.
- It eliminates aggregation, which manifests as thick, structure-free soil.
- Water infiltration is stopped by dispersion over the soil surface, which causes crusting and sealing.

Measures of sodicity

Table 6. Sodic soil tolerant crop varieties

Crops	Varieties	Reference
Hot pepper (chilli)	Chaman, Jawala	(96)
Tomato	Azad T2, Angurlata	
Spinach	Chikari, K Hari	
Garlic	Hansa, Gattar Gola	

- There are either too many plants or trees standing, too few heavy plants, or poor plant development that is below average.
- Differently sized plants.
- Poor rainfall infiltration overhead.
- The shallowness of plants.
- The blockage of the mud channel makes it challenging to immerse oneself outside the study area (72).
- Green or fluctuating water pools.
- The soil is often darker in the shadow because of the intricate development of Na-humic.

Effect of sodicity on vegetables

Like salinity, alkalinity and tolerance vary greatly among plants and their species. When the ESP and salt content in the soil solution are higher than what is allowed for each crop, crop yields are often impacted. Winter crops are often hardier than summer crops in terms of salt tolerance. Therefore, it is suggested that low ET winter vegetable crops (less than 400 mm) can be grown in areas with low rainfall that are categorized as arable crops during the summer. The best course of action would be to select rainfed crops for Kharif and crops that need less water for *Rabi* (94) (Table 7).

Deficits in nutrients and ion toxicities

Sodic soils, which are created by electron and proton activity, may limit the availability of plant nutrients due to limited water and oxygen flow rates, even though high pH levels can remain throughout the soil profile (95). The sodic soils of IGP have been discovered to exhibit significant deficiencies in OM, accessible N, Ca and Zn. Sodic soils often have low levels of nitrogen and organic carbon (OC). Despite the advantages of applying organic inputs like farmyard manure (FYM), regenerated soils lack organic matter (OC) (96).

Chemical amendments

Sodic conditions need the use of tillage, amendments and Na^+ leaching in crop cultivation. By applying chemicals, industrial wastes, composts, microbial inoculants and polymers, sodic soils' physico-chemical properties are improved. The most often utilized chemical to get beyond structural and nutritional constraints is gypsum. However, there is a growing shortage of high-quality agricultural-grade gypsum, which has raised interest in inexpensive, environmentally friendly soil conditioners for reclamation projects (97, 98).

Table 7. Vegetable crops tolerance for sodic soil

Less tolerant (ESP < 20)	Semi-tolerant (ESP 20-40)	Highly tolerant crops (ESP > 40)	Reference
Ginger, turmeric, cluster bean, pea and cowpea	Onion, potatoes, ash gourd, radishes, carrots, cauliflower, fenugreek, fennel, tomatoes, garlic and okra	Eggplant, spinach and sugar beets	(96)

Restoration and handling of sodic soils

Gypsum

Gypsum ($CaSO_4 \cdot 2H_2O$), a soluble calcium salt, is widely used to reclaim sodic soils, particularly those with an Exchangeable Sodium Percentage (ESP) below 15. Excess Na^+ may be eliminated by the soil exchange complex because gypsum increases the quantity of interchangeable Ca^{2+} available. In agriculture, gypsum has long been utilized as an ameliorant and as a calcium and sulfur fertilizer. Gypsum has long been used to improve agricultural soil and as a fertilizer for calcium and sulfur. Applying gypsum as a soil conditioner prevents runoff-induced nitrogen depletion and soil erosion (99).

Technology using gypsum beds: In regions where irrigation water contains high levels of sodium carbonate, gypsum-bed technology offers an efficient method to mitigate sodicity. Traditional methods include mixing gypsum into the soil or placing it in irrigation channels wrapped in porous bags. However, using properly designed gypsum dissolving beds yields notably superior outcomes (100). The gypsum-bed technology transports irrigation water via a brick-cement chamber that is filled with a gypsum clod. The size of the chamber is determined by the discharge from irrigation water tube wells and the amount of sodium carbonate that is left over. The water channel is connected to one side, while the water fall box is connected to the other. Ten centimeters above the chamber floor is an iron bar mesh covered with a 2 mm × 2 mm wire net. If farmers make the necessary modifications, they may also turn their tube wells into gypsum rooms. Dissolving and replenishing the gypsum in the chamber is done by sodic water flowing from the bottom (55). There is no change in the rationale for calculating the gypsum required regardless of the application method. On the other side, the method utilized affects the application time. A single basal dosage of the whole amount of gypsum is administered to the soil. Water-applied gypsum does not accumulate in the soil since it is neutralized before application (100).

Regular applications of agricultural wastes like sawdust, rice hulls, sugar mill waste and so on, as well as thick dressings of organic manures, have been shown to be advantageous. Preserving and enhancing the physical characteristics of soil while mitigating the adverse effects of excessively changing salt levels. Whenever possible, organic fluids that are in danger of becoming alkaline should be supplemented with organic materials. But organic modification is ineffective in reducing the negative effects of alkali water without gypsum. Farmyard Manure (FYM) added gypsum to water to boost the yields of knol-khol, bottle gourds, ridge gourds, bitter gourds, eggplants, broccoli, cluster beans, cauliflower and potatoes (94). Gypsum and FYM were added to counteract the adverse effects of alkaline water, which significantly increased crop growth and yield. They reasoned that high pH and alkalinity altered the rhizosphere's physicochemical environment, delaying tuber formation. The low concentration of potatoes might also be attributed to the detrimental effects of salt in the soil solution. The beneficial effects are attributed to improved rhizosphere conditions, better root development and reduced surface crusting caused by carbonate and bicarbonate precipitation (101).

Sulphur

Elemental sulfur and pyrite can be used to reclaim sodic soils, but their effectiveness depends on their complete oxidation to produce sulfuric acid. Sulfur must be oxidized to generate enough sulfuric acid to replace exchangeable Na^+ for it to function as effectively as soluble calcium ions. Therefore, as compared to gypsum or sulfuric acid, sulfur does not yield the optimal outcomes, even in chemically equivalent concentrations (85).

Industrial by-products

Phosphogypsum

Phosphogypsum (PG), an acidic by-product of phosphoric acid production from rock phosphate, contains essential nutrients such as sulfur (S) and calcium (Ca), along with trace contaminants and heavy metals. It has been shown to mitigate subsoil constraints including acidity, aluminium (Al) toxicity, limited nutrient availability and sodicity (102). The application of powdered PG (5 Mg ha^{-1}) greatly increased IR in a sodic soil (ESP = 21) by inhibiting crust formation; it increased from 0.9 mm h1 in the control to 8.3 mm h1 (105).

According to the study, applying PG and $CaCl_2$ with canal water successfully decreased the amount of salt in saline -sodic soil. Total Na^+ and soluble salts were eliminated 90 % by $CaCl_2$, 79 % by PG and 60 % by PG. In both situations, the soil ESP dropped by around 90 %. Because PG was inexpensive, it was regarded as an effective modification (104).

Fly ash

Large volumes of fly ash (FA), a byproduct of coal and lignite-based thermal power plants, are generated annually. In India, approximately 50 % of this FA is utilized by the cement and concrete industries, while innovative applications for the remainder such as soil restoration are being actively explored (105). In sodic soils, the combined application of gypsum and acidic FA has been shown to reduce the SAR, improve nutrient availability, increase saturated HC and enhance soil water retention. For instance, treatment of sodic soil with this combination (initial soil conditions: pH = 9.07, EC = 3.87 dS m^{-1}, Exchangeable Sodium Percentage (ESP) = 26) resulted in significantly higher rice and wheat yields compared to untreated control plots (106). These findings suggest that FA can effectively substitute up to 40 % of the gypsum requirement (GR), offering a sustainable and cost-effective approach for sodic soil reclamation.

Press mud

A by-product of sugar mills, press mud (PM) increases soil surface area (SAR) over untreated soil since it is low in irrigation and high in plant nutrients. Plant growth and biomass output have been reported to increase, which may be explained by improvements in N, P and K contents and decreases in Na^+ in maize roots and shoots (107). When combined with gypsum, PM significantly enhanced zinc (Zn) uptake and rice yields in saline-sodic soils, demonstrating the synergistic effect of organic and chemical amendments (108).

Organic wastes and composts

Organic additives such as mulches and composts enhance the physico-chemical properties of SAS by improving the plants' capacity to exchange cations, hold onto water and access nutrients. Even though these adjustments are less costly than the pricey chemicals (109).

Mulching

Mulching with organic materials and agricultural wastes improves soil organic carbon (OC), promotes the formation of water-stable aggregates and enhances moisture retention. It protects the root zone by reducing erosion caused by runoff, insulating the soil from heat and minimizing water evaporation (110). Straw mulching in brackish water (3-5 g L^{-1}) When compared to treatments without mulch, irrigated wheat-summer maize rotation soils dramatically reduced salt buildup (111). When compared to severely saline-sodic unmulched soils, a 20-year continuous coverage of saline-sodic soils with tephra mulch that was 10-15 cm thick completely reduced salt danger, as seen by notable decreases in EC se and ESP. Reduced evaporation, enhanced water flow, positive changes in the soil moisture regime and limited upward migration of Na^+ and other salts were cited as the reasons for these decreases. During the trial, neither soil received any irrigation (112).

Landform and drainage treatments for wet sodic soils

Approximately 2.46 million hectares of land in India are affected by waterlogged areas, which result in crop root zone saturation and limited air and water flow. Soils in areas impacted by salt have both permanent waterlogging, when water tables are within 2 m and seasonal waterlogging, which is brought on by floods, high rains and drainage congestion. Anaerobic conditions, osmotic stress, salinity and nutritional toxicities can result from subsurface waterlogging, which occurs when water tables are within 2 m. The states of Punjab and Uttar Pradesh have significant tracts of such wet sodic soils (113).

Irrigation scheduling and management

Sodic soil frequently has problems with permeability and infiltration, which leads to inadequate use of rainfall and decreased irrigation effectiveness. Prior to irrigation, adequate leveling is necessary to provide a homogeneous soil surface and avoid high water application depth, low efficiency and water inundation (114). For crops like wheat in particular, sodic soils need different irrigation management timing, depth and frequency than regular soils. Despite its moderate salt tolerance and sensitivity to waterlogging, wheat has demonstrated improved grain yields under optimized irrigation in sodic soils (115).

Maintaining reclaimed sodic soils' productivity

The potential to reclaim and manage degraded sodic lands using simple methods is well recognized. However, challenges such as the declining availability and quality of agricultural-grade gypsum hinder widespread adoption, despite its effectiveness in addressing structural and nutrient limitations in sodic soils (116). A study in Etawah, Uttar Pradesh, revealed that 27 % of 3905 acres of reclaimed sodic land had resodified, indicating soil degradation and reduced crop productivity (117). In the Indo-Gangetic Plains (IGP), poor irrigation practices, suboptimal fertilizer use, excessive tillage and climate variability further degrade soil health and crop yields (118). Nevertheless, the implementation of conservation agriculture practices-particularly within the Rice-Wheat Cropping System (RWCS) has shown promise in reducing production costs, mitigating resource degradation and improving overall productivity and profitability.

Conclusion

Sustainable management of saline and sodic soils is essential to maintain vegetable crop production and ensure long-term soil health. Salinity reduces plant growth and yield, but this challenge can be addressed through the development of salt-tolerant varieties, traditional breeding, biotechnology and grafting of tolerant rootstocks. Although many vegetables like okra, tomato, eggplant, potato and carrot show some level of salt tolerance, further research is needed to classify them accurately based on their tolerance levels. Efficient water management practices, such as using agricultural drainage water for initial soil leaching, can significantly reduce freshwater use. Additionally, the application of gypsum improves soil structure and accelerates salt removal by increasing calcium and magnesium levels and reducing harmful sodium and potassium. Integrating these practices with the cultivation of salt-tolerant vegetables offers a practical and sustainable approach to reclaim and manage saline-sodic soils effectively. This holistic approach not only supports agricultural productivity but also contributes to the resilience and sustainability of agroecosystems in salt-affected regions.

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Authors' contributions

JM, KRV & VJ performed conceptualization; SN, AS & KRV has done formal analysis; KRV, NS, AS, SK, PY & VJ conducted supervision and validation; JM & KRV corrected language.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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