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Soil salinity and salt tolerance of plants

Global scarcity of water resources, ecological pollution and enlarged salinization of soil and water became a noticeable problem at the beginning of the 21st century. Soil pollution caused by industrial and agricultural activities is an environmental problem that poses serious threats to human health and ecosystems. This review provides, firstly soil salinity characteristics and salinity indicators. Secondly, we focused on saline areas in the world and causes of soil salinization. Thirdly, mapping and monitoring of soil salinity areas and improvement measures for saline soil tolerance. Fourthly, effect of salinity stress on plant and plant salinity response was discussed. This review is intended to provide a comprehensive overview on salinization of soil and presenting fundamental information for future research studies.

Keywords: plants, abiotic factors, stress, soil salinity, salt tolerance, salinization, pollution, ion regulation.

Soil salinity characteristics and salinity indicator

Soil is a vital resource for feeding the growing global population. Excess soil salinity poses a significant threat to agricultural production and environmental health [1]. Soil salinity refers to the amount of dissolved minerals and salts in water. NaCl is considered the predominant salt which is the main cause of soil salinity [2], because, during irrigation with water that mainly has calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^{+}), so when the water evaporates, Ca^{2+} and Mg^{2+} directly precipitate into carbonates, leaving Na^{+} as a dominant anion in the soil that inhibits nutrition activities and creates extreme ratios of Na^{+}/Ca^{2+} or Na^{+}/K^{+} in soil [3, 4].

Some of the traditional method employed to check salinity levels includes [5] electrical conductivity (EC), total dissolved solids (TDS), and sodium adsorption ratio (SAR) [6, 7]. However, these measurements are based on visual observation which only provides qualitative information about crops. Electric conductivity (EC) is among the most important laboratory methods that are used for the classification of soil salinity [8]. Based on US Salinity Staff Laboratory reports, the distinguished characteristic of saline soils has EC > 4 dS/mat 25℃, ESP < 15, and pH of the soil reaction < 8.5 [9, 10] (Table 1). Conventional methods of in situ soil sample collection and analysis for soil salinity are labor-intensive, time-consuming, and costly [11, 12]. Remote sensing data and techniques that detect soil salinity more efficiently and economically with the use of rapid tools and techniques allow the mapping of soil salinity. The electric conductivity analysis of saturated soil paste or in aqueous extracts with different soil/water ratios, and spectrometric analysis are employed for characterization of soil salinity [13].

Table 1

EC values for soil salinity classes

Soil salinity class	Conductivity of the Saturation extraction (dS/m)	Effect on crop plant
Non saline	2–4	Salinity effects negligible
Slightly saline	4–8	Yields of sensitive crops may be restricted
Moderate saline	8–12	Only tolerant crops yield satisfactorily
Strong saline	12–16	Only a few very tolerant crops yield satisfactorily
Very Strong saline	>16	

Saline areas in the world

Global scarcity of water resources, ecological pollution and enlarged salinization of soil and water became a noticeable problem at the beginning of the 21st century. But numerous environmental stresses, like high temperatures, excessive winds, flood, drought, and soil salinity have predominately disturbed the yield and cultivation of important agricultural crops [14]. Amongst these, salinity is not only the major environmental factor that limits plant growth and productivity but also become a worldwide enigma [15].

It is estimated that there are about 5.0 billion hectares of total agricultural land area in the world, this accounted for 37 percent of the total land on earth, and nearly 1.5 billion hectares of this total agricultural area (11% of total land) is now arable land used for stable farming of the crops. Munns and Tester (2008) reported that 800 million hectares of land are affected by the salinity problem [16]. Whereas Wang et al. (2011) reported that this figure will reach up to 950 million hectares in 2011 [17]. Based on the latest report about one billion hectares of land, accounting for 10% of the world's arable land and can exceed up to 50% of the world's arable land in the year 2015. These reports clearly indicate that the saline areas are increasing rapidly. This problem is widely distributed in over 100 countries in the world [18] and is worsening in countries like America, China, Hungary, and Australia, and it will become more severe in North Africa, East Africa, the Middle East, East Asia, and South Asia. There are about 320 million hectares of saline affected land in the Asian continent, accounting for about 1/3 of the world. China has more population with less land, moreover, saline land distribution is very wide [19]. There are 100 million hectares of arable land in China, amongst them 6.66 million hectares were polluted with different degrees of salinization [20].

Causes of soil salinization

The land salinization reason can be divided into two 1) Primary (natural) and 2) Secondary (anthropogenic) [21]. It has many reasons to increase naturally:

1. Various rock such as intermediate igneous rocks; basic igneous rocks and undifferentiated volcanic rocks have affected soil salinity. Because when rock salt is freed from the substrate, the upper soil gets precipitated by capillary action and cause soil salinization [22].
2. Climatic changes like annual rainfall, evaporation, temperature, humidity and pH also influenced soil salinity.
3. Soil pore and other physical structures also effect the migration and accumulation of the salinity in the land soil.
4. Entry of seawater during cyclones in coastal areas.
5. Vegetation coverage.
6. Seasonal and gradient influence of major projects on the occurrence of soil salinization.
7. A significant proportion of the recently cultivated agricultural land has become saline because of the use of poor-quality water for irrigation and improper drainage in a canal-irrigated wetland agro-ecosystems [23, 24]. These serious consequences represent the decreasing of productive agricultural land for farming [25].

Mapping and monitoring of soil salinity areas

The necessity of mapping soil salinity

Population pressure is increasing in the world and about 20% of the world's total cultivated area and nearly 50% of the irrigated croplands are heavily affected by soil salinity [26]. In the near future, more dry lands will be put into agriculture for crop production. Therefore, it is important to monitor and map saline areas, at an early stage to enact an effective soil reclamation program that helps to lessen or prevent the future increase in soil salinity [27, 28].

The technology used for soil salinity mapping

Scientists monitored or map the soil salinity by taking Remote Sensing Data through salt features (white salt crusts) that are visible at the soil surface, and the presence of halophytic plants. These methods are known as soil reflectance indicators and vegetation reflectance indicators [9]. Remote sensing technology helps to get information about objects or areas from a long distance by aircraft or satellites (http://oceanservice.noaa.gov/facts/remotesensing.html). It has been used in different research fields such as archeological research [29], ecosystem services [30], medical sciences [31], environmental research [32], abiotic stress studies [33]. Advantages of using remote sensing technology include providing the multispectral images, saving time, wide-coverage, (satellite remote sensing provides the only source when data is required over large areas or regions), faster than ground methods, and facilitating long-term monitoring [9]. However, in soil salinity studies, only considering soil reflectance may not be enough to measure variation in soil salinity, because, the spatial variability of soil salinity over the landscape is highly sensitive and is controlled by a variety of factors. These factors include:

1. Soil factors (surface roughness, moisture, parent material, permeability, water table depth, groundwater quality, and topography);

2. Management factors (irrigation and drainage);

3. Climatic factors include (rainfall and humidity) [8, 34]. Therefore, it is beneficial to use vegetation reflectance as an indirect indicator for mapping soil salinity, because it can provide a spatial overview of salinity distribution and avoid limitations associated with the direct use of soil reflectance [35].

The use of vegetation reflectance as an indirect indicator

Vegetation reflectance has been used in numerous fields, including ozone [36, 37], soil contamination [38–41], pathogens, senescence, dehydration, natural gas and metal contamination.

Indicator plant species have been generally used together with physical and chemical indicators to determine soil salinity [7], but not all can be good remote sensing indicators of soil salinity [9]. Plant communities were better indicators soil salinity than individual species, the dominant halophytic communities in saline areas. For examples, *Salicornia europaea* community and *Aster tripolium* community were present at salinity over 20 mS/cm, *Triglochin maritima* community over 12 mS/cm, *Puccinellia distans-Salicornia europaea-Spergularia marina* community over 8 mS/cm and *Glaux maritima-Potentilla anserina-Agrostis stolonifera* community over 2 mS/cm [42].

Additionally, the performance of some salt tolerance crops such as alfalfa, barley, and cotton can provide the severity of soil salinity. Alfalfa is an ideal natural resource and model plant for remediation of contaminated soils, offering a variety of elite characteristics, including a highly productive biomass, drought tolerance, a fast-growing and prosperous root system, and availability in large amounts over several months of the year [43]. Cotton is basically cultivated on irrigated land, so it is considered an ideal indirect indicator for soil salinity and has been used as salinity indicators in a variety of studies [9, 44]. For example, Zhang et al (2011) reported that the vegetation cover of Yellow River Delta (YRD) of China, includes some grass species: suaeda (*Suaeda glauca*), Suaeda salsa, aeluropus (*Aeluro- pus sinensis*), cogon grass (*Imperata cylindrica*), reed (*Phragmites*), and a shrub species: saltcedar (*Tamarix chinensis*), crops planted in the YRD are salt-tolerant varieties, including cotton (*G. hirsutum*) and corn (*Zea mays*). The dominant species in the YRD could represent typical halophytic plants and salt-tolerant crops because they are also common in other saline areas [35].

Improvement measures for saline soil tolerance

To improve saline soils, it was attempted three main measures:

1. Chemical improvement measures. Liu et al. (2015) did experiment to study the effects of newly-developed ameliorant, gypsum and cow in the coastal saline-alkali soil of north Jiangsu Province [45]. The authors measured the plant (*Salicornia europea* L.) growth and ion concentration in stems and roots. The results of this study presented that the three ameliorants, including cow dung, gypsum, new ameliorant and their combinations developed soil chemical and physical contents and moreover confirmed to improve the total plant height and stem diameter in the following order of manure usage: cow dung > gypsum > new ameliorant.

2. **Biological and ecological measures.** Microorganisms with the following characteristics like salt tolerant with improved genetic variability, synthesizing compatible solutes, producing plant growth promoting hormones, bio-control potential, can successfully interacts with the crop plants to improve the saline soil quality [14]. In the microbiological investigations of saline soils, great attention has been paid to the halophilic, osmotolerant, and alkalo tolerant microorganisms [46]. For example, Salt-tolerant plant growth-promoting rhizobacteria (ST-PGPR) significantly influence the growth and yield of wheat crops in saline soil, it is beneficial bacteria that live in the plant root zone [47]. Plants treated with rhizobacteria have better root and shoot growth, nutrient uptake, hydration, chlorophyll content, tolerance to diseases, higher K^+ ion concentration and, in turn, a higher K^+/Na^+ ratio that favors salt tolerance [48].

3. **Introduction of salt tolerance plants.** Increased salt tolerance of perennial species used for fodder or fuel production is an important and natural method for controlling the spread of secondary salinity. However, different crop species have different threshold tolerance ECe and yield reduction rate [24] (Table 2). If salt levels are 0 to 2 dS/m, yield of the most crops are not significantly reduced; a level of 2 to 4 dS/m affects

some crops; whereas most of the crops are significantly affected when salt levels ranges from 4 to 5 dS/m [49]. ECes around 7.7, 12, and 17 dS m−1 are classified into low, moderate and high salinity level, respectively. Cotton is one of the advantageous salt tolerant crop with a threshold salinity level of 7.7 dS/m−1 (equal to 0.5% or 77 mmol/L NaCl), but, the germination of cottonseed and emergence of seedling is generally delayed and reduced by high salinity levels [50]. At present, China has the largest saline soil area in the world used for cotton farming. According to the incomplete statistics, the plant cotton saline area is about 1.7 billion hm^2 [17].

Table 2

Many important crops are susceptible to soil salinity

Crop	Threshold salinity	Decrease in yield
	dS m-1	Slope % per dS m-1
Bean (*Phaseolus vulgaris* L.) Eggplant (*Solanum melongena* L.) Onion (*Allium cepa* L.) Pepper (*Capsicum annuum* L.)	1.0 1.1 1.2 1.5	19.0 6.9 16.0 14.0
Corn (*Zea mays* L.)	1.7	12.0
Sugarcane (*Saccharum officinarum* L.)	1.7	5.9
Potato (*Solanum tuberosum* L.)	1.7	12.0
Cabbage (*Brassica oleracea var. capitata* L.)	1.8	9.7
Tomato (*Lycopersicon esculentum* Mill.)	2.5	9.9
Rice, paddy (*Oryza sativa* L.)	3.0	12.0
Peanut (*Arachis hypogaea* L.)	3.2	29.0
Soybean （*Glycine max* L.) Wheat (*Triticum aestivum* L.)	5.0 6.0	20.0 7.1
Sugar beet (*Beta vulgaris* L.) Cotton (*Gossypium hirsutum* L.)	7.0 7.7	5.9 5.2
Barley (*Hordeum vulgare* L.)	8.0	5.0

Effect of salinity stress on plant and plant salinity response

Effect of salinity stress on plant

Under salinity stress conditions, soluble salts are accumulated in the root zone of plants [49], than causes osmotic and ionic stress [51]. We can see the two-phase model relating the osmotic and ionic effects of salt stress below (Fig. 1).

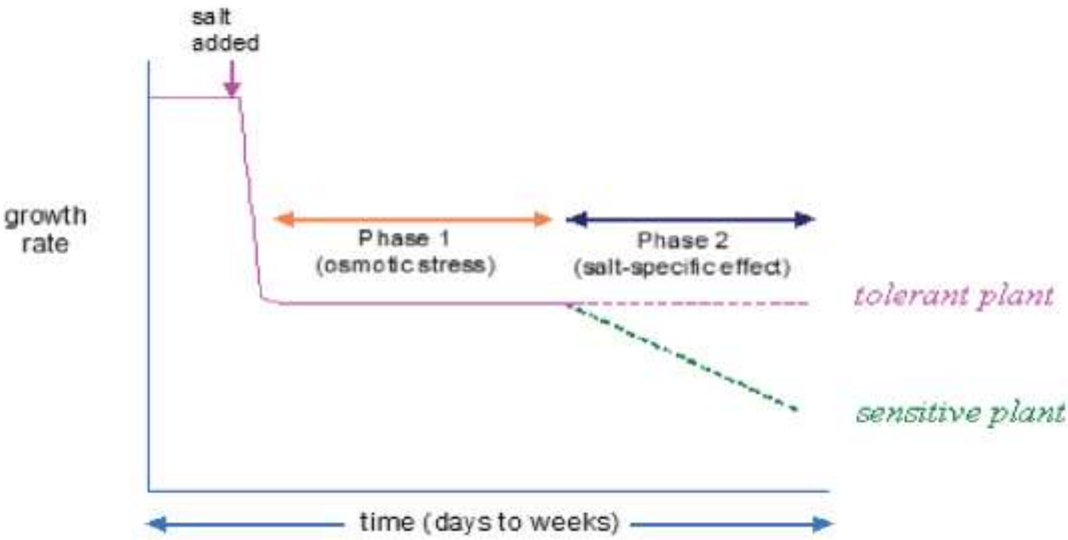

Figure 1. Scheme of the two-phase growth response to salinity [53]

In the first, osmotic effect starts rapidly after the salt concentrations especially Na and Cl level increases more than a threshold level and there is decrease in K, Ca, NO_3 and Pi concentrations in the root zone. Osmotic stress resulted in decrease water availability for the plant cells which leads to a decrease water uptake with cellular dehydration. Subsequently the rate of shoot growth falls significantly, moreover with the decrease rate of growing leaves expansion, slower rate of leaves emergence and slow lateral buds' development with fewer branches or lateral shoots formation. This non-specific effect is common to all dehydrative stresses including salinity, drought, and low temperatures and with some types of mechanical plant wounding [22]. The ion-specific effect is a secondary phase of the plant response to salinity, whereas higher levels of salt get accumulated in the older leave parts and resulted in cell death. Hence, with the decrease in new leave production due to more leave necrosis, the photosynthetic rate of plants decreased having lower levels of carbohydrates, which is required for new leave production [52, 53].

Plant salinity response mechanism

Plants differ in their ability to cope with these adverse factors. Depending on growth performance of these organisms in saline habitats, plants can be divided into two groups: salt-sensitive "glycophytes" and salt-tolerant "halophytes" [54]. Halophytes can complete their whole life cycle at salt concentrations higher than 200 mM NaCl [22], even can survive salinity in 300–400 mM extra salt concentration [52]. Some halophytic Amaranthaceae (*Salicornioideae, Chenopodioideae and Suaedoideae*) yield is significantly negatively affected at low salt concentrations, because their growth rate is stimulated at a salinity range of 150–300 mM NaCl [55]. Glycophytes, including most crop plants not only reduce their yield in high salt concentration, but also are killed by 100–200 mM NaCl [52].

Generally, three major factors determine the tolerance of plants to extreme environmental conditions (abiotic stresses) at molecular level:

1. **Genomic level:** Plants have differences at genome structure level, it is suggested that salt tolerant plants may have unique stress-responsive genes, which sensitive plants do not have.
2. **Transcriptomic level:** Tolerant plants have altered gene expression regulation features of stress-responsive genes than salt sensitive plants. Tolerant plants may enhance constitutive expression of several salinity-responsive transcripts. Enhanced constitutive expression of several salinity-responsive transcripts (SOS1, SOD, P5CS, GS, INPS, cytochrome P450, heat shock protein).
3. **Proteomic level**: Plants has differences in protein structure and activity level, thus proteins involved in the stress responses revealed an altered activity in tolerant plant than in susceptible ones because of the (differences in protein structure and activity level) [56].

Plants developed a combination of biochemical and molecular mechanisms to cope with salt stress situation. The specific biochemical strategy undertaken by plant is: (1) ion regulation and compartmentalization, (2) induced biosynthesis of compatible solutes, (3) induction of antioxidant enzymes, which are illustrated in figure further down (Fig. 2) [57].

Ion regulation and compartmentalization

Na+ enters roots passively, through voltage-independent nonselective cation channels and possibly through other Na+ transporters such as some members of the high-affinity K+ transporter (HKT) family [16] and may also block the K — specific transporters of root cells under salinity [24]. For plant development Ionic uptake and compartmentalization are key factors, most importantly during salt stress because of disturbance of ion homeostasis. Glycophyte or halophyte cannot tolerate higher salt in the cytoplasm, thus they restrict the excess salts in the vacuole or compartmentalize the ions in other plant tissues to carry out normal metabolic functions. Glycophytes also inhibit the sodium uptake or partition sodium that served as storage compartments and then die. Plants maintained low levels of cytosolic sodium levels by regulation of potassium and sodium transporters and H+ pumps that generate the driving force for transport of ions across the membranes [51]. To cope salinity, drought, cold, acid stress, anoxia, and excess heavy metals stress in the soil, survival of the plant cells solely depends on the maintenance or adjustment of the V-ATPase activity. Na+ stress is well known to cause Ca++ depletion in the extracellular space and the outer surface of the plasma membrane, whereas increased extracellular Ca++ also help to up regulates the cytosolic free calcium levels.

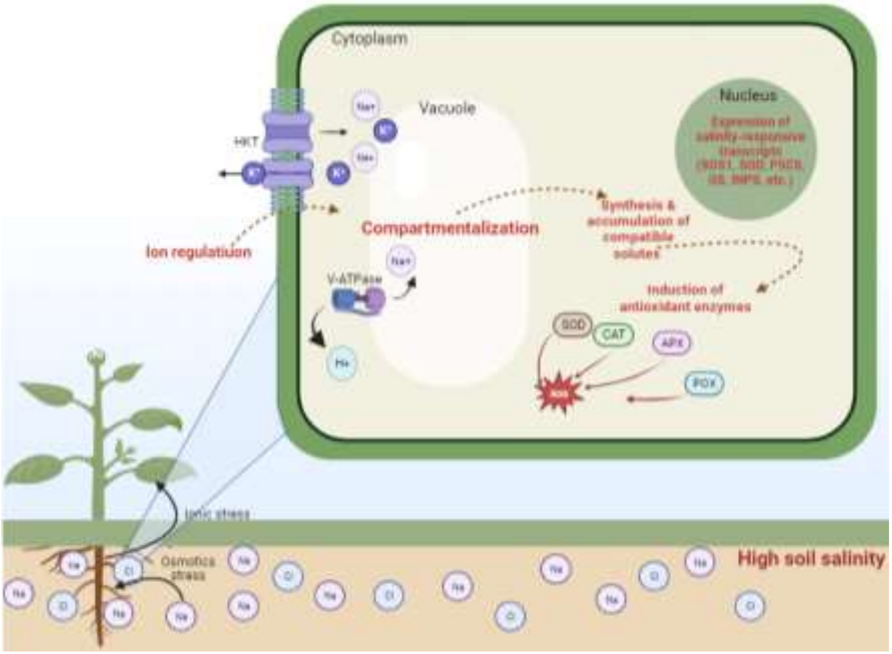

Figure 2. Plant response mechanism to salt stress (Illustration created on biorender.com platform)

Induced biosynthesis of compatible solutes

The accumulation of compatible solutes is often regarded as a basic strategy for the protection and survival of plants under abiotic stress conditions. These compatible solutes include mainly proline, glycine betaine (GB), sugars, and polyols [58–61]. Multiple functions for these compounds have been suggested. The conventional role of these compatible solutes is to maintain cell osmotic adjustment and reduce the water potential in high salinity condition [62]; they are also suggested to act as low- molecular-weight chaperones, stabilizing the photosystem II complex, protecting the structure of enzyme, proteins and inducing damages to cellular component, maintaining membrane integrity and scavenging ROS [58].

Induction of antioxidant enzymes

Salt, drought, heat and oxidative stress are related to an enhanced production of reactive oxygen species (ROS) such as O2, H2O2, and OH [63]. These ROS can cause damage to the cellular membranes, function of photosynthetic apparatus, activities of various enzymes, and peroxidation of lipids. Salt-tolerant plants, besides being able to regulate the ion and water movements, should also have better antioxidation strategies to scavenge these toxic compounds [64]. These antioxidants (ROS scavengers) include enzymes such as catalase, superoxide dismutase (SOD), ascorbate peroxidase (APX) and glutathione reductase; non-enzyme molecules such as ascorbate, glutathione, carotenoids, and anthocyanins; compounds, such as osmolytes, proteins (e.g. peroxiredoxin) and amphiphilic molecules (e.g. tocopherol) [63, 65]. The antioxidants have been found to be key determinants of salt tolerance in different crops. For example, in order to determine whether cell membrane permeability, activities of antioxidant enzymes such as SOD, CAT and POX and K+ vs. Na+ selectivity criteria for salt tolerance in canola (*Brassica napus* L.) four lines, Dunkled, CON-III, Rainbow and Cyclone. RMP was found to be associated with the activities of antioxidant enzymes, SOD, CAT and POX and the lines differ significantly for shoot K+/Na+ ratios and shoot K+ vs. Na+ selectivity, but these traits prove not good indicators for salt tolerance in the canola. Overall relative cell membrane permeability and activities of antioxidant enzymes (SOD, CAT and POX) proved to be very effective in discriminating the canola cultivars for salt tolerance [66, 67] reported that the activities of antioxidant enzymes and lipid peroxidation were associated with the dry mass production and consequently with the salt tolerance of the three maize cultivars [67]. Where in another study superoxide dismutase (SOD) activity increased significantly in both genotypes, and increases in amounts of transcript were observed for OsSOD3Cu/Zn and OsSODA1-Mn in the tolerant genotype and for OsSOD4-Cu/Zn, OsSOD3-Cu/Zn, OsSODCc1-Cu/Zn, OsSOD-Fe, and OsSODA1-Mn in the sensitive genotype [68].

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Топырақтың тұздылығы және өсімдіктердің тұзға төзімділігі

Су ресурстарының жаһандық тапшылығы, қоршаған ортаның ластануы және топырақ пен судың тұздануының жоғарылауы XXI ғасырдың маңызды мәселесінің бірі. Өнеркәсіптік және ауылшаруашылық жұмыстарынан туындаған топырақтың ластануы адам денсаулығы мен экожүйеге үлкен қауіп төндіретін экологиялық мәселе. Мақалада біріншіден, топырақтың тұздану сипаттамалары және тұздану көрсеткіштері ұсынылған. Екіншіден, әлемнің тұзды аймақтарына және топырақтың тұздану себептеріне назар аударылған. Үшіншіден, топырақтың тұздану аймақтарын картаға түсіру және бақылау мен топырақтың тұздануға төзімділігін арттыру шаралары қарастырылған. Төртіншіден, тұзданудан туындаған күйзелістің өсімдіктерге әсері және өсімдіктердің тұздануға реакциясы талқыланған. Мақаланың мақсаты — топырақтың тұздануына жан-жақты шолу жасау және болашақ зерттеулер үшін негізгі ақпаратты ұсыну.

Кілт сөздер: өсімдіктер, абиотикалық факторлар, күйзеліс, топырақтың сортаңдануы, тұзға төзімділік, ластану, тұздану, иондардың ретелуі.

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Засоленность почвы и солеустойчивость растений

Глобальная нехватка водных ресурсов, экологическое загрязнение и возросшее засоление почвы и воды стали заметной проблемой начала XXI века. Загрязнение почв, вызванное промышленной и сельскохозяйственной деятельностью, представляет собой экологическую проблему, представляющую серьезную угрозу здоровью человека и экосистемам. В обзоре представлены, прежде всего, характеристики засоления почв и показатели засоления. Во-вторых, мы сосредоточили внимание на засоленных территориях мира и причинах засоления почв. В-третьих, рассмотрели картирование, мониторинг зон засоления почв и меры по повышению устойчивости почв к засолению. В-четвертых, обсуждалось влияние стресса, вызванного засолением, на растения и реакцию растений на засоление. Целью этого обзора является предоставление всестороннего обзора засоления почв и фундаментальной информации для будущих исследований.

Ключевые слова: растения, абиотические факторы, стресс, засоление почвы, солеустойчивость, загрязнение, засоление, регуляция ионов.

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