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REVIEW ARTICLE

Use of Lower Quality Water in Irrigated Agriculture and Effects on Forages with Productive Potential in Semiarid Regions: a Review

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Abstract

In the agricultural sector, using lower quality water sources has increased in irrigation practice. Thus, this review summarizes the consequences of using brackish and/or saline water in irrigated agriculture, highlighting some effects on soil and plants in general. Water quality for irrigation and the salinity tolerance threshold of forage species with productive potential for semiarid regions are also discussed. Between January and June 2022, a systematic search was carried out for studies that evaluated the quality of water for irrigation, the effects of using water with excess salts on the soil and on plants in general, and on forage species with productive potential in semiarid regions. The databases consulted were: ScienceDirect, Scopus, Wiley Online Library, Web of Science, Taylor and Francis, and Scholar Google. A total of 1567 studies were found. Of these, 200 studies were reviewed and 154 were used because they met the review objective. The forage plants reported here have salinity tolerance ranging from low to moderate. The management adopted, as well as the species used, are factors that influence the performance of the crop under stress. Although they are widely cultivated in arid and semiarid regions of the world, few studies still show the salinity threshold of these crops, mainly for forage cactus, sunflower, and pigeon pea species. Therefore, it is essential to carry out more research on this topic in order to provide information that improves the management of production systems in saline environments around the world.

Highlights

- Forage species have tolerance ranging from low to moderate.
- The management adopted and the species influence the performance of the crop under stress.
- Sorghum and millet are the most tolerant species studied.
- Some practices lessen the effects of salinity on forage plants.

Keywords Forage cactus · Grasses · Osmotic stress · Salinity · Tolerance

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1 Introduction

The scarcity of good quality water resources is a problem that affects the entire world, with a greater impact in areas with arid and semiarid climates, where rainfall is irregular and atmospheric demand is high (Norton-Brandão et al. 2013; Yasuor et al. 2020). In the agricultural sector, this problem has increased the use of unconventional sources of water for irrigation, such as groundwater and wastewater of inferior quality, which in most cases, have high levels of salts that can negatively affect the soil and plants (Yasuor et al. 2017; Cheng et al. 2021). Ions such as sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), and carbonate (CO_3^{2-}) are among the most harmful to crops because, at relatively high concentrations in irrigation water, they can accumulate in the soil and inhibit the full growth of plants (Zörb et al. 2018; Köster et al. 2018).

It is estimated that more than 830 million hectares of land are affected by salinity, and this value tends to grow even more (Minhas et al. 2020; FAO 2022). Soil salinity is a global problem that threatens the ability of soils to produce, and estimates reveal that around 50% of all arable land will be impacted by salinity by 2050 (Butcher et al. 2016). Thus, strategies that help in the management of soils affected by salts, and better management of inferior water used in irrigation, should be prioritized and favor more sustainable agriculture. The use of saline stress-tolerant plants (i.e., halophytes), irrigation methods and frequency, as well as the application of leaching depths associated with an efficient drainage system are examples of practices that can minimize the effects of salinity within the production system (Yasuor et al. 2020; Minhas et al. 2020).

Salt stress is one of the abiotic factors that mostly limits the growth and productive potential of crops (Minhas et al. 2020). In general, most commercially important plants are sensitive to salt, as they have a relatively low salinity threshold, showing a significant decrease in growth and yield when exposed to an initial salinity condition of 1.0 to 2.5 dS m^{-1} of soil saturation extract (ECe) (Zörb et al. 2018; Yasuor et al. 2020). On the other hand, forage plant species with productive potential in semiarid regions (e.g., cactus, sorghum, millet, pigeon pea, and sunflower) have low to moderate salinity tolerance (Singh et al. 2015; Freire et al. 2018; Souza et al. 2021; Jardim et al. 2020a, b; Salvador et al. 2021).

The response of plants to salinity occurs in two distinct phases (Munns and Tester 2008). The first, called the osmotic phase, occurs when salts (e.g., Ca^{2+}, K^+, Na^+ and Cl^-) reach the roots, decreasing the osmotic potential of the soil–plant interface, making water absorption difficult. The second phase, called ionic, occurs when the salt, at high concentrations, reaches the aerial part of the plant, causing toxicity and, consequently, leaf death. This significantly reduces the photosynthetic rate of the plant, causing a decrease in growth and productivity, as well as the quality of the raw material produced (Munns and Tester 2008).

After exposure to salt stress, osmotic reactions in plants occur at an accelerated rate, and the toxicity of the ions present in the medium has several consequences (Julkowska and Testerink 2015; Yasuor et al. 2020). For example, excess Na^+ in the soil, in addition to reducing water absorption, can cause an imbalance of nutrients in plants, by reducing the absorption of K^+, Ca^{2+}, and Mg^{2+} by the roots, due to ionic antagonism (Zörb et al. 2018). On the other hand, the high content of Cl^- in irrigation water can cause changes in the uptake and use of nitrate (NO_3^-) by the crop, causing negative effects on its development (Yasuor et al. 2020). Furthermore, high levels of salts, especially Na^+, can accelerate the degradation of soil structure (Martínez-Alvarez et al. 2016; Qadir et al. 2021).

The responses of forage plant species to saline stress are variable. In addition, there is little information on the tolerance of some species, such as forage cactus, sunflower and pigeon pea. Considering the increasing use of water with high salt content in irrigation, mainly in semiarid regions, this review presents a summary of the consequences of the use of lower quality water in irrigated agriculture. The effects of salinity on soil and plants are described, as well as the quality of irrigation water and salinity tolerance of forage species with productive potential in semiarid regions.

2 Literature Review

2.1 Method

Between January and June 2022, a search was carried out for studies that evaluated the use of lower quality water in irrigated agriculture. The main focus of the research was the quality of water for irrigation, the effects of using water with excess salts on the soil and plants in general, and on forages with productive potential in semiarid regions. For this, the following databases were used: 1—ScienceDirect, 2—Scopus, 3—Wiley Online Library, 4—Web of Science, 5—Taylor and Francis and 6—Scholar Google, without application of date and language restrictions for the studies. Keywords used were: low quality water, irrigation, salinity, forage plants, plants, salinity tolerance, saline soil, salinity, forage cactus, forage sorghum, forage millet, pigeon pea, forage sunflower, water quality, effects of salinity, salinity tolerance mechanisms and saline stress were used in the search, both individually and combined with each other by the Boolean operator "AND", forming 20 search strings.

A total of 1567 studies were found, the majority being in the Google school database (Fig. 1). Of these, 200 studies were reviewed, and 154 met the criteria to meet the objective of this review. The works included were published between 1954 and 2022 (Fig. 2).

Then, the sessions discussed in this review were defined: Water quality for irrigation, Effect of salts on soil and plant, and Tolerance of forage plant species to salinity. The latter, with emphasis on the responses of forage cactus (*Opuntia* spp. and *Nopalea* spp.), forage

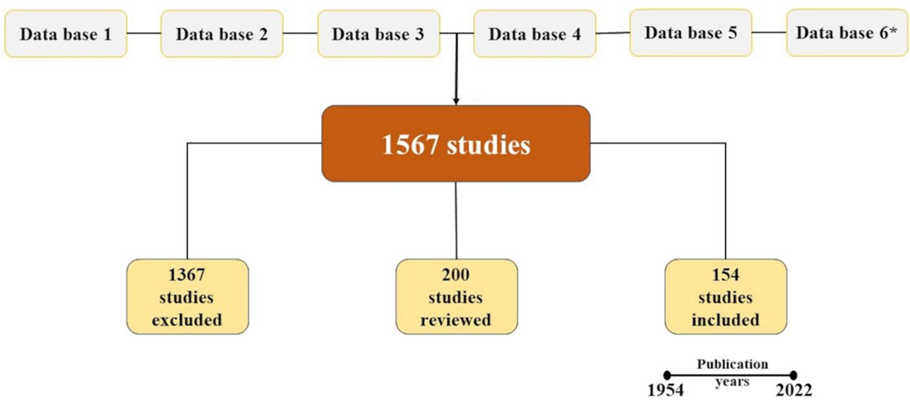

Fig. 1 Flowchart of procedures for inclusion of studies used in the review. *Database (Google Academic) with the highest number of results found

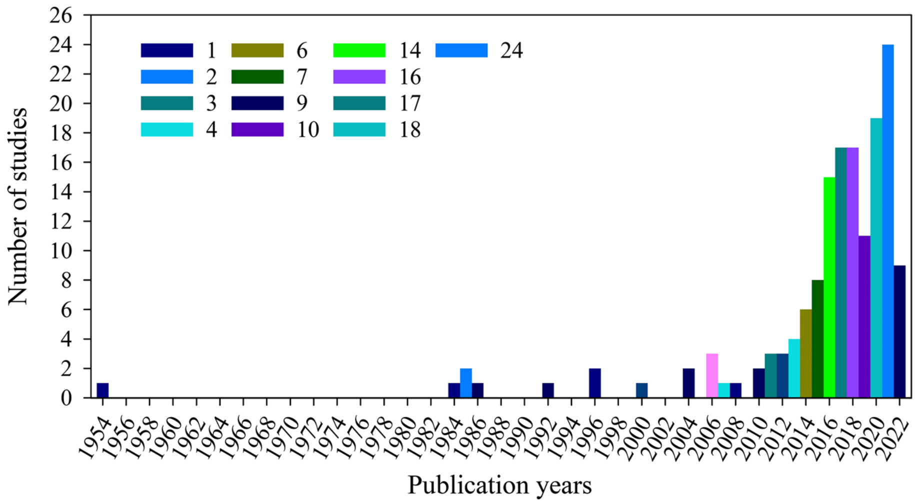

Fig. 2 Number of articles per year of publication used in the review

sorghum [*Sorghum bicolor* (L.) Moench], forage millet (*Pennisetum glaucum L.*), forage sunflower (*Helianthus annuus L.*), and pigeon pea [*Cajanus cajan (L.) Mill sp.*] species, submitted to saline stress conditions.

3 Results and Discussion

3.1 Water Quality for Irrigation

Rapid population growth, increased demand for food, climate change, and the intensification of agricultural activities impose strong pressure on non-renewable natural resources, mainly soil and water. For this reason, freshwater scarcity is increasingly becoming one of the main global problems, being an obstacle to the development of sustainable agriculture (Gharaibeh et al. 2016; Zaman et al. 2018). According to the United Nations Organization (UNO), it is estimated that by 2050 the world population will increase from 7.6 billion to more than 9 billion, with a large part of this population being present in underdeveloped countries, where water scarcity and food production are already striking problems (Bortolini et al. 2018; Zaman et al. 2018). For this scenario, a 70% increase in current agricultural productivity is predicted to be necessary for the global demand for food to be met (Zaman et al. 2018). Thus, better water management for irrigation is crucial to achieving satisfactory crop yields, as well as improving the efficient use of water resources (Queiroz et al. 2016; Pereira et al. 2020). In addition, efforts are also needed to better capture and conserve rainwater for agriculture, especially in arid and semiarid regions, where the effects of climate change are more pronounced (Zaman et al. 2018; Punia et al. 2020). On the other hand, the existing water limitations in these regions evidence the need to seek alternative sources of water (Lemos et al. 2021).

The use of water of lower quality, whether underground and/or wastewater (e.g., saline water, treated domestic sewage, brackish water, desalinated water, among others), has been gradually increasing in irrigated agriculture (Norton-Brandão et al.

2013; Libutti et al. 2018; Al-Reyami et al. 2020; Cakmakci and Sahin 2021). This is a promising alternative, as in addition to improving food production, it can significantly reduce the demand for high-quality water (Carvalho et al. 2021). However, its use, without proper management, can cause problems of toxicity to crops, negative effects on the soil, spread of parasites, and damage to the irrigation system (Bortolini et al. 2018). For these reasons, there are concerns about the agricultural use of these waters, which encompass aspects of human and environmental health (Norton-Brandão et al. 2013). Therefore, its usability in agriculture also depends on the adoption of agronomic practices that mitigate its adverse effects, its characteristics, and, consequently, its quality (Bortolini et al. 2018; Minhas et al. 2020; Carvalho et al. 2021).

The quality of water used in irrigation is one of the factors considered for the proper management of water and nutrients in agricultural production systems. Generally speaking, water quality standards are seen as a relatively broad topic, which includes a large number of guidelines or regulations that vary according to the end use of water. However, when related to irrigation, the characterization of the quality of water resources initially comprises the knowledge of the water sources available for this purpose (e.g., fresh water, saline/brackish water, wastewater, and desalinated water), as well as, the type of crop, irrigation system used and water quality parameters, with emphasis on salinity (Norton-Brandão et al. 2013; Lothrop et al. 2018; Yasuor et al. 2020).

Many parameters are used in the evaluation of water quality; however, the concentration and composition of the salts present in the water determine its usability for different purposes, such as for human, animal, and irrigation (Bortolini et al. 2018; Zaman et al. 2018). For the latter, according to Zaman et al. (2018), there are four basic criteria for assessing water quality:

- The total soluble salts (salinity hazard);
- Relative proportion of sodium ions (Na^+) to calcium Ca^{2+} and magnesium (Mg^{2+}) – sodium adsorption ratio (sodicity risk);
- The concentration of residual sodium carbonate anions (RSC) – bicarbonates (HCO_3) and carbonates (CO_3^{2-}) concerning Ca^{2+} plus Mg^{2+} ions, and
- The excessive concentrations of sodium (Na), Boron (B) and chloride (Cl^-) that cause ionic imbalance or toxicity in plants.

Among the mostly used references to characterize and, thus, define the quality of water for irrigation, is the classification of the United States Salinity Laboratory (Richards 1954) and the FAO (Food and Agriculture Organization of the United Nation) (Westcot and Ayers 1985). Regarding the classification of Richards (1954), a diagram (Fig. 3) is used to classify the waters, being divided into four classes (C1 to C4), considering the electrical conductivity (EC_w), i.e., as a function of the concentration of total soluble salts, and another four classes (S1 to S4), according to their sodicity, based mainly on the effect that exchangeable sodium has on the physical condition of the soil. The combination of these two indices, EC_w and SAR, makes it possible to establish different types of water, each one being identified by the initial of each of the numerical indices and sub-indices. As the value of the sub-indices increases, the quality of irrigation water decreases. Table 1 presents the meaning and restrictions of use for each class of water according to Richards (1954) classification.

This classification is widely used today, although later studies have shown some drawbacks. For example, Pizarro (1985, 1996) pointed out the main problems of this

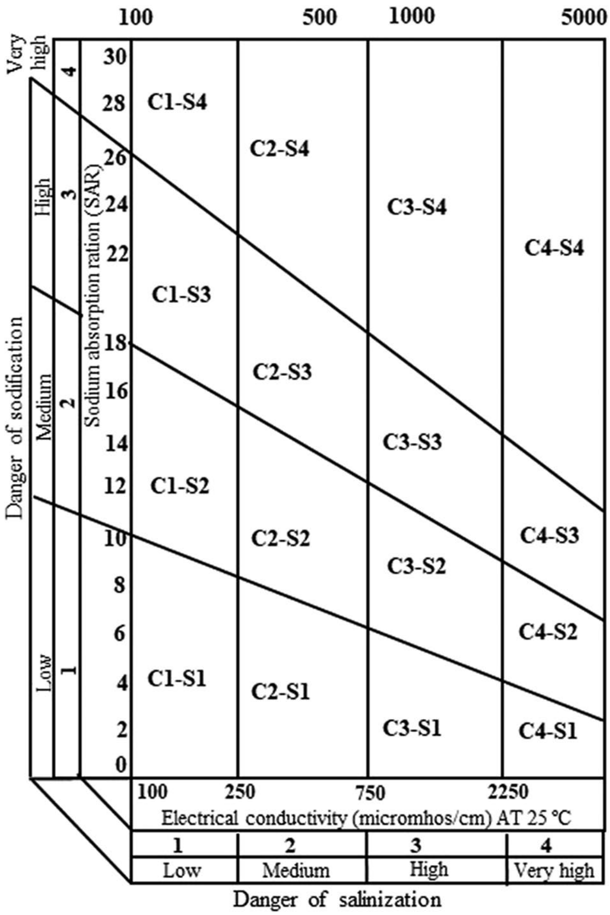

Fig. 3 Richards diagram for interpreting water for irrigation purposes (adapted from Richards 1954)

classification: a) The assumption that Ca^{2+} and Mg^{2+} have the same ion exchange selectivity, which does not correspond to reality; for the same SAR, the adsorption of Na + increases when the Mg/Ca ratio increases due to the lower energy of adsorption of Mg^{2+}; b) It does not take into account the possibility of salt precipitation, a phenomenon that can increase the risk of sodicity since Ca^{2+} is the cation mostly subjected to reaction, precipitating in the form of carbonate and sulfate that are of low solubility; and c) The classification has a conceptual error since the salts in the soil solution have a flocculating effect, opposite to the dispersing effect of exchangeable sodium; thus, for the same SAR, the risk of sodicity will be lower for higher EC_w.

Thus, the descending lines in the classification diagram become ascending according to Fig. 4, therefore, of the sixteen predicted classes of the combination of salinity and sodicity in the classification of Richards (1954), six do not exist under natural conditions.

In the classification proposed by Westcot and Ayers (1985), the quality of water used in irrigation practice is related to potential problems that can be caused, which are subdivided into four groups (Table 2).

Table 1 Meaning and restrictions on the use of water classes for irrigated agriculture, according to Richards (1954)

Class and type of water	EC_w (µS cm^{-1}, 25 °C)	Restrictions on use
C_1 – Low salinity water	0 – 250	It can be used in irrigation practice on most crops, on almost all soil types, with a low probability of salinity development. Despite this, it needs small leaching depths, which can be achieved under normal irrigation conditions
C_2 – Average salinity of water	250 – 750	When there is a moderate degree of leaching, its use is not restricted. Plants with moderate salinity tolerance can be grown
C_3 – High salinity water	750 – 2250	Restricted for irrigated agriculture in soils with inefficient drainage. Under adequate drainage conditions, it is recommended to adopt practices to control salinity, in addition to the cultivation of plants very tolerant to salts
C_4 – Very high salinity water	2250 – 5000	Restricted for irrigation, however, in critical conditions of water deficit, its use can be an alternative. For these conditions, the soils must have good permeability and adequate drainage, to facilitate the leaching of salts. Salinity tolerant plants should be used
Class and type of water	SAR	Restrictions on use
S1 – Low sodium water	$SAR \leq 18.87 – 4.44 \log EC$	Can be used for irrigation in most soils, with a low possibility of reaching critical levels of exchangeable sodium. However, sensitive crops can accumulate harmful amounts of it
S2 – Water with average sodium content	$18.87—4.44 \log EC < SAR \leq 31.31—6.66 \log EC$	It has some restrictions on use in fine textured soils. On the other hand, they can be used in coarse textured soils and/or organic soils with good permeability
S3 – Water with high sodium content	$31.31—6.66 \log EC < SAR \leq 43.75—8.87 \log EC$	It can produce toxic levels of exchangeable sodium in most soils, requiring special management practices, good drainage, easy leaching, the input of organic matter, as well as the application of soil conditioners (e.g., gypsum)
S4 – Water with very high sodium content	$> 43.75 – 8.87 \log EC$	Restricted for irrigation, except when salinity varies from low to moderate and the use of soil conditioners is economically viable

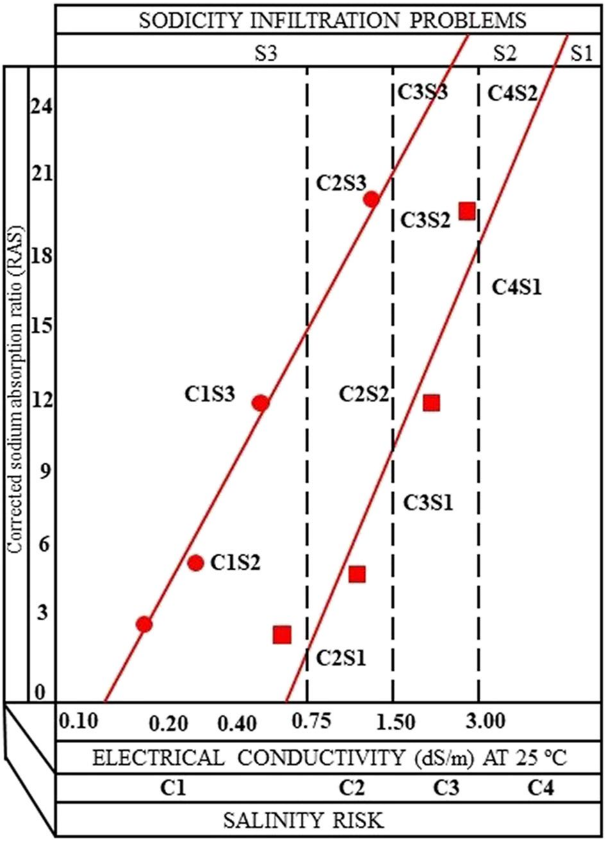

Fig. 4 Approximate diagram of water classes for irrigation (adapted from Pizarro 1996)

3.2 Effect of Salts on Soil and Plant

The exploitation of water with high levels of salts can overcome the scarcity of quality water for irrigation. However, the use of this water can induce, when poorly managed, salinization of the soils, with consequent negative effects on the development and growth of the plants (Yasuor et al. 2020; Cheng et al. 2021; Feng et al. 2021).

Soil salinization is a term that includes saline, saline-sodic, and sodium soils, which are characterized, respectively, as: 1 – soils that present high concentrations of salts, which can be converted to non-saline soils by leaching the soluble salts present in the root zone; 2 – soils with high concentrations of Na^+; and 3 – soils with high pH, mainly due to the high concentration of CO_3^{-2} (Richards 1954; Daliakopoulos et al. 2016). Soil salinity is classified based on the electrical conductivity of the soil saturation extract (ECe) and the relative Na^+ content, which in turn is obtained by RAS (Eq. 1) or exchangeable sodium percentage (ESP) (Eq. 2) (Richards 1954; Butcher et al. 2016; Carabali et al. 2019). In general, saline soils have an ECe equal to or greater than 4 dS m^{-1} (Table 3), which is equivalent to approximately 40 mmol L^{-1} of NaCl or an osmotic potential of -0.2 Mpa (Rengasamy 2006; Köster et al. 2018). In turn, soil sodicity is characterized by high SAR or ESP (Table 3) and accumulation of Na^+ concerning Ca^+ and Mg^+ (Rengasamy 2010; Cucci et al. 2013).

Table 2 Guidelines for interpreting water quality for irrigation (Westcot and Ayers 1985)

Potential problem	Unit	Degree of use restriction		
		None	Mild to moderate	Severe
Salinity (affects the availability of growing water) EC or	dS m^{-1}	< 0.7	0.7 – 3.0	> 3.0
Dissolved solids content—DSC	mg L^{-1}	< 450	450 – 2000	> 2000
Infiltration (reduces seepage; assess using SAR and EC)				
SAR = 0 – 3 and EC =	dS m^{-1}	< 0.2	0.2 – 0.7	> 0.7
3 – 6 and EC =	dS m^{-1}	< 0.3	0.3 – 1.2	> 1.2
6 – 12 and EC =	dS m^{-1}	< 0.5	0.5 – 1.9	> 1.9
12 – 20 and EC =	dS m^{-1}	< 1.3	1.3 – 2.9	> 2.9
20 – 40 and EC =	dS m^{-1}	< 2.9	2.9 – 5.0	> 5.0
Specific ion toxicity (Affects sensitive crops)				
Sodium (Na^+)				
Surface irrigation	SAR	< 3	3 – 9	> 9
Sprinkler irrigation	meq L^{-1}	< 3	> 3	
Chlorine (Cl^-)[4]				
Surface irrigation	meq L^{-1}	< 4	4.0 – 10	> 10
Sprinkler irrigation	meq L^{-1}	< 3	> 3	
Boron (B)	mg L^{-1}	< 0.7	0.7 – 3.0	> 3
Various (affects sensitive crops)				
Nitrogen (NO_3 N)	mg L^{-1}	< 5	5.0 – 30	> 30
Bicarbonate (HCO_3) (foliar spray only)	mg L^{-1}	< 1.5	1.5 – 8.5	> 8,5
pH		Normal range 5.5 – 8.4		

Table 3 Characteristics of salt-affected soils

Property of the soil	Unit/Symbol	Types of soils affected by salts		
		Saline	Saline-sodic	Sodic
Electric conductivity	ECe (dS m^{-1})	> 4	> 4	< 4
Exchangeable sodium percentage	ESP	< 15	< 15	> 15
pH	-	< 8.5	< 8.5	> 8.5
Sodium absorption ratio	SAR	< 13	< 13	> 13

Source: Richards (1954)

$$\mathrm{SAR} = \frac{\mathrm{Na^+}}{\frac{\sqrt{\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}}}}{2}} \tag{1}$$

$$\mathrm{ESP} = \frac{\mathrm{Na^+} \times 100}{\mathrm{CEC}} \tag{2}$$

where Na^+, Ca^{2+}, and Mg^{2+} refer to the concentration of sodium, calcium, and magnesium, respectively, in the soil, in mg L^{-1}, and CEC is the cation exchange capacity of the soil, that is, the number of negative charges present in the soil, in $mmol_c\ dm^{-3}$.

Soil salinity is a widespread problem affecting over 424 million hectares of topsoil (i.e., 0–30 cm) and 833 million hectares of subsoil (i.e., 30–100 cm) worldwide, with significant effects on about 20% of the entire irrigated area (Negrão et al. 2016; FAO 2022). Considered one of the greatest threats to soil degradation, this process can be due to primary and secondary causes (Daliakopoulos et al. 2016).

Primary salinization is caused by the natural accumulation of soluble salts from the parent rock, which occurs due to physical or chemical weathering and transportation of the original material, deposition of geological materials, and elevation of saline groundwater (Daliakopoulos et al. 2016; Yasuor et al. 2020). This process often occurs in arid and semiarid regions, where rainfall distribution and occurrence are low and atmospheric demand is high. For this reason, primary salinization is also called dryland salinity (Yasuor et al. 2020). On the other hand, secondary salinity is a result of human effects, especially irrigation with saline water and/or irrigation with saline/brackish water and/or inadequate irrigation associated with inefficient drainage conditions (Daliakopoulos et al. 2016; Singh 2019; Jardim et al. 2020b; Yasuor et al. 2020).

The high concentration of salts can cause serious problems to the soil, such as changes in its physicochemical properties, reduction in hydraulic conductivity and infiltration, as well as in the water potential (i.e., an increase in osmotic potential) (Daliakopoulos et al. 2016; Perri et al. 2020; Li et al. 2022). In conditions with high levels of Na^+, for example, the degradation of the soil structure and, consequently, a decrease in the movement of water and air in its environment processes are frequently observed (Rengasamy 2010). This is due to the dispersion and expansion of clay, which in turn blocks soil macropores and reduces its permeability (Nouri et al. 2017).

With reduced infiltration, the availability of nutrients and water becomes restricted to plants, in addition to increasing the risks of flooding, susceptibility to erosion, and surface runoff from the soil (De La Paix et al. 2013). On the other hand, when the soil is dry, surface crusts are formed due to the obstruction of the pores by small clay particles, which hinder the hydraulic conductivity of the soil environment (Daliakopoulos et al. 2016; Nouri et al. 2017).

In the case of soils with high concentrations of Ca^+ and Mg^{2+}, changes in pH are observed (Zörb et al. 2018; Köster et al. 2018). The higher the concentration of these ions, the higher the pH of the soil, with significant effects on its fertility and physical–chemical properties. The large variation in water content is another recurring problem, which becomes a limiting factor for productivity (Deinlein et al. 2014). The high levels of soluble salts present in the medium increase the osmotic pressure, significantly reducing the availability of water and the absorption of nutrients by the plants (Deinlein et al. 2014). In addition, processes such as decomposition and respiration are negatively impacted by the increase in soil ECe (Singh 2016). The decomposition of organic matter is affected due to changes in the microbiological community of the soil, as osmotic stress can cause microbial cell lysis, with consequent accumulation of cellular solute and reduction in the population of microorganisms (Singh 2016). In summary, breathing is altered due to increased CO_2 emissions caused by high salinity. According to Singh (2016), fewer microbes breathe more and decompose readily available organic molecules under saline stress. Thus, the CO_2 produced can be dissolved in the soil solution and underestimate its evolution. Singh (2016) also points out that, in sodic soils, the dissolution of calcium carbonate ($CaCO_3$) forms CO_2, which can overestimate respiration. Therefore, the effects of salinization can result in the loss of resources, goods, and services from the soil and, consequently, impact local sustainability and agricultural production, with possible sociocultural and human health problems (Daliakopoulos et al. 2016; Nikalje et al. 2017; Yin et al. 2022).

In agricultural areas with salinity problems, glycophytic plants (i.e., plants sensitive to salinity) have difficulty maintaining their full growth and development (Perri et al. 2018; Ayub et al. 2020). The effects of salinization on crop growth and productivity include increased osmotic stress, which affects water and nutrient uptake, the toxicity of ions, or even the accumulation of specific ions in the aerial part of plants (Julkowska and Testerink 2015; Minhas et al. 2020). The high concentration of salt in the soil creates a high osmotic potential that reduces water availability for plants. Decreased water potential causes osmotic stress, which inactivates photosynthetic electron transport. In addition, the loss of cell turgor promotes stomata closure, which in turn decreases CO_2 fixation and, therefore, effects on plant growth, development, and productivity are observed (Safdar et al. 2019).

In general, the plant response to salinity can be described in two phases, the first characterized by the independent plant response to ions and, the second when the observed effects are induced by specific ions (Negrão et al. 2016). The first phase occurs quickly, ranging from minutes to days after initial contact with saline stress (Julkowska and Testerink 2015). In this phase, the water relationships of plants undergo significant changes, causing stomatal closure, inhibition of leaf development, and physiological drought (Negrão et al. 2016; Nouri et al. 2017). The latter is caused by ions dissolved in the soil solution near the roots, which create a water potential difference at the soil–plant interface, making it difficult for the root system to absorb water (Ayub et al. 2020). On the other hand, the second phase develops for a longer period (i.e., days to weeks) and the accumulation of ions at toxic levels in the aerial part of the plant is a striking feature, inducing leaf senescence and, consequently, the reduction of the final yield or even the death of the plant (Negrão et al. 2016).

In conditions of high salinity, the first reactions can be observed in the reduction of the germination potential of the seedlings; however, the most evident effect is the delay in the growth and development of the plants (Minhas et al. 2020). Toxic responses are initiated when Na^+ ions enter the epidermal and cortical cells of the roots, through non-selective cation channels, leading the plant to several perturbations (Julkowska and Testerink 2015; Yasuor et al. 2020).

High concentrations of Na^+ and Cl^-, especially in the cytosol, have significant consequences on the absorption of cationic elements (e.g., K^+, Ca^{2+}, and Mg^{2+}), as well as on the nutritional imbalance of the plant, mainly due to the interaction with nitrate (NO_3^-) (Yasuor et al. 2020). High levels of Na^+ and Mg^{2+} can destroy cell morphology, reduce chlorophyll production and thereby restrict photosynthesis (Daliakopoulos et al. 2016). In addition, in response to salt stress, plants show significant production of reactive oxygen species (ROS), such as singlet oxygen ($^1O_2$), superoxide (O^{2-}), hydroxyl radical (OH^-), and hydrogen peroxide (H_2O_2), which in turn cause oxidative damage to cells, interfering with vital plant cell functions (Gupta and Huang 2014).

To deal with salinity stress, plants develop some physiological and biochemical mechanisms capable of mitigating the effects of salinity (Ayub et al. 2020). Among the many, there are: homeostasis and ion compartmentation; transport and absorption of ions; biosynthesis of osmoprotectants and compatible solutes; activation of antioxidant enzymes; synthesis of polyamines and antioxidant compounds; nitric oxide production, and hormonal modulation (Gupta and Huang 2014). However, it is worth noting that plants may have variable tolerances to salinity, depending on the soil type, types of rhizobacteria, growth stage, and agronomic practices (Daliakopoulos et al. 2016).

The adoption of some management practices within production systems is an alternative to maintain, at satisfactory levels, the growth, development, and production of plants under saline stress conditions. For example, in the cultivation of *Cucumis sativus* L. subjected to irrigation with different levels of NaCl, Cao et al. (2016) observed that the use of a straw biological reactor decreased salinity and improved soil chemical properties, reducing Na^+ accumulation in the shoots and roots of plants, with a significant increase in nutrient uptake and crop growth. Yield and fruit quality were also improved with the use of technology. In tomato cultivation in an arid environment, under irrigation with water with different EC_w, Li et al. (2022) obtained good results in fruit quality. In this study, the authors adopted drip irrigation management under the regulation of the levels of salts in the irrigation water and observed, in addition to the good quality of the fruits, an acceptable concentration of salts in the soil over two years of cultivation.

3.3 Tolerance of Forage Plant Species to Salinity

Salinity tolerance refers to the ability of plants to withstand concentration of soluble salts present in the soil solution, without affecting their growth, development, and productivity; in turn, it is specific to each culture (Minhas et al. 2020). The following is a brief report on the salinity tolerance of some forage plant species that have great production potential in agricultural systems in a semiarid environment.

3.3.1 Cactus Forage (*Opuntia* spp. and *Nopalea* spp.)

Cactus (*Opuntia* spp. and *Nopalea* spp.) is an important forage resource for arid and semi-arid regions. Despite the low concentration of dry matter (5–15% DM), crude protein, and fiber, attributes such as high digestibility, high levels of soluble carbohydrates, and water reserve make this crop a viable food alternative for herds (Araújo Júnior et al. 2021a; Dubeux Júnior et al. 2021). In the Brazilian semiarid, for example, the species commonly cultivated are the Orelha de Elefante Mexicana—OEM (*Opuntia stricta* Haw. (Haw.)), Ipa Sertânia—IPA (*Nopalea cochenillifera* (L.) Salm-Dyck), and Miúda—MIU (*Nopalea cochenillifera* (L.) Salm-Dyck), mainly due to their resistance to carmine mealybug (*Dactylopius opuntiae* Cockerell, 1929, Hemiptera: Dactylopidae), which are considered the main pest of the crop (Araújo Júnior et al. 2021b).

Due to its morphophysiological characteristics, the cactus forage can adapt to conditions with high air temperatures and water scarcity, maintaining a good production of green phytomass even during periods of long drought (García-Nava et al. 2015; Queiroz et al. 2015). Its photosynthetic metabolism, called Crassulacean acid (MAC), gives it excellent efficiency in the use of water since CO_2 capture occurs at night when the air temperature is lower and the loss of water through transpiration is minimal (Scalisi et al. 2016). In addition, its succulent stems (i.e., cladodes), responsible for photosynthesis and with a high capacity to accumulate water, low number of stomata, thick cuticle, and an adapted root system are other characteristics that make it adapt to adverse conditions (Hassan et al. 2019). Although it is adapted to a large number of growing conditions, its tolerance to saline environments is little reported in the literature (Gajender et al. 2014). Considering that salinity is one of the abiotic factors that most limit plant growth and productivity, this information is extremely important for the proper management of the crop (Freire et al. 2021).

The adaptation of forage cactus to salinity and, consequently, its productive potential under these conditions, vary according to the clones cultivated (Freire et al. 2018). According to Inglese et al. (2017), even with characteristics that give it the ability to adapt to various cultivation environments, the species *Opuntia fícus-indica* (L.) Mill is sensitive to high soil salinity and waterlogging, due to the lack of air in the root zone caused by these conditions. The cactus root system has low dry mass production, which restricts its development in saline environments (Snyman 2004). In this sense, the cultivation of this species in soils with ECe > 4 is not indicated (Inglese et al. 2017).

The use of saline water in irrigation causes, in addition to salinization, variations in soil pH throughout the crop cycle, which is normally associated with the alkalinity of the water, which in turn can be a result of the concentration of bicarbonates (Porto Filho et al. 2011). Although most crops can tolerate a wide pH range (Zaman et al. 2018), forage cactus may have reduced growth, as reported by Gajender et al. (2014), who, when evaluating three clones of *Opuntia fícus-indica* (L.) Mill submitted to three salinity levels (0, 32, and 52 mM), observed that the cactus species was tolerant to the salinity of 52 mM (EC ~ 5 dS m^{-1}), but they found sensitivity at pH equal to 9.8, with negative effects on plant growth. However, Singh (2004) evaluated different soil pH (8.1, 8.4, 8.7, 9.4 and 10) in cactus pear cultivation, and observed different effects on the culture's growth dynamics. For example, at pH 8.1, the sprouting of cladodes started at 54 days after planting (DAP), while at pH 10 it was observed at 90 DAP. From pH 8.7, the plants showed a lower rate of shoots, as well as reduced size and mass of cladodes. Given these findings, indicating an ideal pH range for cactus pear cultivation becomes difficult. The performance of the crop under different salinity conditions may vary according to the species and the management adopted in the production system, and not just the stress applied.

In plants of *Nopalea cochenillifera* Salm Dyck submitted to irrigation with saline water with EC_w (3.6 dS m^{-1}), Freire et al. (2018) observed a reduction in the amount, thickness, and width of cladodes, as well as a decrease in forage yield, possibly due to a large number of salts absorbed by the plant in relation to other conditions (0.3, 0.5, and 1.5 dS m^{-1}). The effects of salinization on crop growth and productivity include increased osmotic stress, which affects water and nutrient uptake (Minhas et al. 2020). In this sense, the difficulty in capturing water by the roots favors the decrease in the thickness and width of the cladodes, significantly reducing the growth of the forage cactus (Scalisi et al. 2016). Therefore, the variation in cladode thickness may be indicative of plant dehydration (Inglese et al. 2017), which in turn may be due to the osmotic effect. Characteristics such as the quantity, size, and distribution of cladodes in the plant influence the photosynthesis of the crop and, consequently, its productivity (Araújo Júnior et al. 2021b).

Irrigation with saline water can result in adverse effects on the soil–water-plant interface, causing negative effects on the productive potential of plants. Furthermore, toxic effects of salinity can be observed if the concentrations of salts present in plants are above their tolerance levels (Dias et al. 2016). The use of irrigation with saline water with EC_w ranging from 1.5 to 3.6 dS m^{-1} caused greater damage (i.e., dehydration and chlorosis) to basal, primary, and secondary cladodes of *Nopalea cochenillifera* Salm Dyck (Freire et al. 2018).

In a study with 20 forage cactus species (*Opuntia* and *Nopalea*) irrigated with water with EC_w (3.6 dS m^{-1}), Freire et al. (2021) observed that the species forage Liso (*Opuntia fícus-indica* (L.) Mill) took 419 days to reach score 5 (i.e., severe damage) in relation to the other species, indicating its greater tolerance to salinity. However, in terms of dry matter yield, this clone presented the lowest results (36.1 g $plant^{-1}$) compared to Orelha de Elefante Mexicana (*Opuntia stricta* (Haw.) Haw) (51.5 g $plant^{-1}$), and Orelha de Elefante Africana (*Opuntia undulata* Griffiths) (50.8 g $plant^{-1}$), showing that, despite not showing high tolerance to the imposed conditions, the Orelha de Elefante Mexicana and Orelha de Elefante Africana can be an alternative for forage production in these environments (Freire et al. 2021).

In conditions irrigated with saline water (EC_w – 1.5 dS m^{-1}), in the Brazilian semi-arid region, the clone Orelha de Elefante Mexicana showed higher productivity in relation to clones of the genus *Nopalea* (Miúda and Ipa Sertânia), both in green mass and in dry mass (Araújo Júnior et al. 2021b). According to Freire et al. (2018), cactus species of the genus *Nopalea* have a low tolerance to salt stress. Thus, the findings by Araújo Júnior et al. (2021b) may be indicative of greater tolerance to the saline environment of clones of the genus *Opuntia* than the genus *Nopalea*.

As seen, the salinity tolerance of forage cactus can vary, among other factors, according to the cultivated species. On the other hand, the expression of metabolites such as dehydrins and the accumulation of compounds may contribute to the tolerance of cactus to abiotic stresses (Ochoa Alfaro et al. 2012). In addition, parameters such as total chlorophyll content in young and old cladodes, chlorophyll-a content in old cladodes, and total soluble sugars present in the roots can be used to identify the tolerance of *Opuntia* species to salt stress (Lallouche et al. 2017). Mechanisms such as ion retention through selective root transport and carbon balance through CAM metabolism are other possible reasons why cacti tolerate saline soils (Nobel et al. 1984).

3.3.2 Sorghum Forage (*Sorghum bicolor* (L.) Moench)

Sorghum is a forage species belonging to the Poaceae family, originating in Africa and distributed throughout the tropical and subtropical regions of the world (Jardim et al. 2020a; Pennells et al. 2021). It is considered the sixth most cultivated food in the world, and the fifth cereal with the highest economic value, being, in many parts of the world, the staple food for many rural communities and people with food insecurity (Punia et al. 2019; FAOSTAT 2022) .

Its C4 photosynthetic metabolism gives it high efficiency in water use and drought tolerance (Pennells et al. 2021; Pinheiro et al. 2021) and characteristics such as rapid growth, resistance to water deficit, tolerance to lodging, high production of biomass, geographic adaptation and easy cultivation from seeds, make this crop an important alternative for the development of sustainable technologies in the most diverse areas (e.g., bioenergy, biofuels, food, and feed, among others) (Nghiem et al. 2016; Stamenkovic et al. 2020).

Characteristics such as high forage and agronomic potential (i.e., low water requirement and regrowth potential), linked to its chemical attributes (i.e., source of energy and fiber, high production of dry mass and crude protein) make the cultivation of sorghum and its use for animal feed, one of the strategies adopted by producers in arid and semiarid regions, being in many situations a partial or total substitute for corn in the formulation of rations (Samarappuli and Barti 2018). In addition, its salinity tolerance is another attribute that makes it an important food resource for these regions (Chakravarthi et al. 2017; Punia et al. 2021; El-Mageed et al. 2021).

Although considered tolerant to saline stress, some sorghum cultivars, in the early stages of development, are sensitive to this condition (El-Mageed et al. 2021). The stages of germination and emergence of seedlings of this forage are considered the most informative of the crop cycle to identify salinity tolerance (Dehnavi et al. 2020). Bafeel (2014) evaluated seven sorghum cultivars (C1, C2, C3, C4, C5, C6, and C7) subjected to irrigation with seawater (i.e., dilutions of Red sea water at 1.65, 3.1%, 6.3%, 12.5%, 25%, 50% and 100%), and observed that seeds irrigated with 100% saline water did not germinate after three days of exposure to the treatment. On the other hand, when submitted to irrigation with 50% saline water, all seeds of three cultivars (C1, C3, and C5) germinated, a result not observed for cultivars C2, C4, C6, and C7, which showed germination ranging from 77 to 97%. These results show that the physiological responses of the plant subjected to salinity, among other factors, vary according to the cultivar used (Ali et al. 2020). Similar results were obtained by Coelho et al. (2018). Ali et al. (2020), when studying the effects of saline irrigation (0, 2.5, 5.0, 7.5, 10 and 12.5 dS m^{-1}) on ten genotypes of forage sorghum (F305, BRS-655, BRS-610, Volumax, 1015045, 1016005, 1016013, 1016015 and 1016031), observed different responses in plant photosynthesis and transpiration, with the F305 genotype showing the worst performance. Factors such as growth, development, and duration of exposure to stress can also be determinants of plant tolerance to salinity (Munns and Tester 2008).

Salt stress tolerance in the early stages of development determines a better establishment of the crop in the field, and the characteristics observed in the seedlings are a valid criterion for the selection of more salt tolerant sorghum genotypes (Dehnavi et al. 2020). The growth and development of the root system and shoot, as well as the weight of the plant, can decrease significantly due to salt stress (Bafeel 2014). When evaluating the initial growth of 10 sorghum genotypes submitted to four levels of NaCl (0, 100, 150, and 200 mM), Dehnavi et al. (2020) observed that salinity reduced the percentage of germination, root length, shoot length of the seedling, and the fresh and dry mass of the seedlings, with different responses between the genotypes studied. Dehnavi et al. (2020) point out that factors such as reduced water imbibition, osmotic stress, alterations in enzymatic activities, which affect hormonal balance and reduce seed reserves, and an increase in phenolic compounds, can be decisive to reduce the germination process under saline stress. In addition, salinity can inhibit the maintenance of essential nutrients for the growth of roots and shoots of seedlings. In turn, the toxic effect of Na^+ on photosynthesis, due to the reduction in CO_2 concentration and stomatal closure, reduces the fresh and dry mass of seedlings. Another factor is that Na ions can decrease the rate of transport of essential ions (e.g., NO_3^-), which reduces the amount of nitrogenous compounds, with consequent inhibition of both plant growth and biomass accumulation. On the other hand, under moderate salinity conditions (i.e., 3 to 5 dS m^{-1}), some sorghum cultivars may show good initial shoot growth (Coelho et al. 2018). This result corroborates the salinity limit value (ECe = 6.8 dS m^{-1}) by Maas (1986), who classified sorghum as moderately tolerant to saline stress.

Regarding the productive potential of the crop, studies carried out in the semiarid region of Brazil showed the good productive performance of the crop under irrigation water salinity conditions ranging from 1.4 to 1.6 dS m^{-1}. For example, Jardim et al. (2021), when evaluating three sorghum cultivars (2502, IPA-SF11, and IPA-467) in an exclusive and intercropped system under irrigation with high salinity water (i.e., C3, according to Richards classification 1954), obtained average green matter yields equal to 221.73 Mg ha^{-1} (cactus + sorghum) and 145.92 Mg ha^{-1}, respectively. Diniz et al. (2017) obtained average yields of 62.01 kg ha^{-1} of green mass and 14.07 kg ha^{-1} of dry mass, for the cultivar SF-15 in an exclusive system under different water regimes with saline water. On the other hand, under rainfed conditions, Perazzo et al. (2013) obtained yields ranging from 37.17 to 52.14 kg ha^{-1} in green mass, and 10.88 to 14.51 kg ha^{-1} in dry mass, when studying five cultivars of sorghum (Ponta Negra, SF-15, IPA 1011, IPA 2502 and IPA 46742). These results show that irrigation with water of lower quality can be an alternative for the cultivation of forage sorghum in Brazilian semiarid conditions. However, in addition to productivity, the quality of the forage produced must be taken into account, as it has a direct influence on the digestive functions and health of the animals (Chakravarthi et al. 2017).

In this sense, when evaluating 23 genotypes and 300 sorghum lines subjected to different salinity levels (60, 80, 100, 120, and 150 mM NaCl), Punia et al. (2021) reported an influence on the nutritional quality of the forage produced, with a reduction in protein content and dry matter digestibility, with increased levels of NaCl, and considerable accumulation of hydrocyanic acid under the same conditions. Reductions in plant height and accumulation of dry matter, decreasing the amount of forage, were also reported by these authors.

In general, sorghum tolerance to salinity may be related to the exclusion of Na^+ from the aerial part of its plants (Krishnamurthy et al. 2007), as well as to the high concentration of soluble sugars in the leaves, which exert significant activity of osmoregulation in this culture (Coelho et al. 2018). High photochemical quantum yield, high chlorophyll content, high relative water content, and a higher chlorophyll stability index can also confer salt tolerance in sorghum plants (Punia et al. 2021). In addition, the application of exogenous hormones (e.g., jasmonic acid, humic acid, and gibberellic acid) can reduce the adverse effects of salinity on the development of this crop (Nimir et al. 2014; Ali et al. 2020). The application of phytohormones in seed treatment, such as jasmonic acid, can increase the diffusion of water into the cell, improve oxygen absorption, and increase a-amylase activity and the transfer of nutrients from cotyledons to embryos, favoring a higher seed germination rate (Nimir et al. 2014). In summary, the exogenous application of gibberellic acid can mitigate the effects of NaCl in several cultures, due to the activation of catabolizing enzymes or by blocking the biosynthesis pathway of abscisic acid, which is responsible for seed dormancy under stress conditions (Nimir et al. 2015). On the other hand, humic acid can be easily absorbed by plants, and thus, favors the absorption of nutrients (e.g., nitrogen and phosphorus) (Elmongy et al. 2018) which improves crop performance under stressful conditions (Nimir et al. 2014).

3.3.3 Millet Forage (*Pennisetum glaucum L.*)

The millet (*Pennisetum glaucum* L.) belongs to the Poaceae family, is considered the sixth most consumed cereal in the world, being the staple food of the low-income rural population, mainly in arid and semiarid areas of India and China (Dias-Martins et al. 2018; Yousaf et al. 2021; Mitharwal et al. 2021). Such importance is due to the high nutritional value of the crop, which has high levels of essential amino acids, crude protein, fat, ash, energy, calcium, and iron in its composition compared to other cereals such as wheat, corn, and rice (Souza et al. 2019; Mitharwal et al. 2021).

Since its introduction in Brazil in 1929 in Rio Grande do Sul, millet has been widely used as a ground cover in no-till and as fodder in animal feed (Dias-Martins et al. 2018). The latter, mainly in the semiarid region, is due to the great potential for biomass and grain production, when compared to other crops that have reduced yields due to the climatic peculiarities of the region (Santos et al. 2017). Millet produces considerable amounts of biomass even when subjected to conditions of low water availability, and may, for example, be an alternative to corn to feed livestock (Bergamaschine et al. 2011; Alonso et al. 2017; Bhattarai et al. 2020). In addition, the nutritional composition and low production cost are other factors that favor its use in the Brazilian semiarid region (Alonso et al. 2017). However, it is worth mentioning that drought tolerance varies for each cultivar (Santos et al. 2017).

This species has C4 metabolism, which favors its cultivation in environments where high air temperatures and water deficit are outstanding characteristics (Souza et al.

2019; Bhattarai et al. 2020; Wilson and Vanburen 2022). In addition, the crop is well adapted to conditions of low soil fertility and high salinity (Singh et al. 2015; Souza et al. 2021). A wide variation in salt stress tolerance can be found in several genotypes of this species, and varieties native to arid and semiarid regions may show better responses to stress conditions when compared to new cultivars (Jha 2022).

Millet responses to salinity depend on its genetic makeup and environmental conditions (Jha et al. 2021). Considering the valuable genetic resource that some varieties of this species can present, some studies have used millet genes to confer salinity tolerance to other species, such as rice and peanuts (Tripathy et al. 2017; Rao et al. 2017). However, it is worth mentioning that, although it is tolerant to salinity conditions, recent research has shown significant reductions in grain and forage yields of this crop. For example, under high salinity conditions, with levels ranging from 8 to 12 dS m^{-1}, Yadav et al. (2020) observed reductions of 13 to 22.43% in the final grain yield. Decreases of 19 and 41.3% were observed by Toderich et al. (2018) on biomass and grain yield, respectively, in 11 millet lineages.

The performance of plant species under stress conditions must be evaluated through existing characteristics among the tolerant genotypes, as well as by the plant development stage, to select individuals that present better responses to salinity (Jha et al. 2021). In this sense, observing the growth characteristics in the initial stages of crop development is essential, since good responses to high salt concentrations in these stages can be predictive of a good establishment of the adult plant under salinity conditions (Uddin et al. 2017; Dehnavi et al. 2020).

After selecting the most productive lines in the field, Toderich et al. (2018) observed that when subjected to increasing salinity levels (100, 200, 300, and 400 mM NaCl) in the initial growth phase, the selected strains, IP 19586 and HHVBC Tall, showed tolerance to osmotic stress, but not to stress from ionic acid at the seedling stage. However, IP 19586 was less affected by salinity than HHVBC Tall, due to the higher content of proline and malondialdehyde (MDA), proving to be a good alternative for cultivation under the conditions studied.

In a study with 33 millet genotypes at an early stage of development, submitted to four salinity levels (50, 75, 100, and 150 mM NaCl) during 7, 14 and 21 days of exposure to stress, Jha et al. (2021) identified two highly tolerant genotypes, 18 with moderate tolerance and 13 salt-sensitive. Under these conditions, the authors observed a higher content of osmolytes and antioxidant enzymes in the highly tolerant genotypes, which may indicate a better response to salinity. Thus, osmotic adjustment and scavenging of free radicals may be the main mechanisms controlling millet tolerance at saline conditions (Jha et al. 2021).

Plants can present several stress tolerance strategies, such as osmotic adjustment, compartmentalization of toxic ions, and ROS homeostasis, through significant changes in their gene expression, which in turn can trigger changes in protein levels, leading to phenotypic and/or physiological changes in plants (Mahmoud and Abdelhameed 2021; Jha 2022). Furthermore, the application of plant bioregulators such as salicylic acid and thiourea, in addition to improving millet growth, development, and yield, can minimize the adverse effects of salt stress on the crop (Yadav et al. 2020).

3.3.4 Sunflower Forage (*Helianthus annuus L.*)

Sunflower (*Helianthus annuus* L.) is an oilseed crop belonging to the Asteraceae family, native to North America, being traditionally cultivated to produce edible oil (Sinha et al. 2017; Ebrahimian et al. 2019). The plants contain 40 to 50% oil, which consists of unsaturated fatty acids and vitamin E, with good nutritional quality, which makes it a great option for human consumption. In addition, the significant protein values, which range from 17 to 20%, make the crop a good alternative for animal feed production (Sinha et al. 2017; Hussain et al. 2018; Ebrahimian et al. 2019).

Sunflower has C3 metabolism and is well adapted to regions with arid and semi-arid climates, where it is normally cultivated under rainfed conditions or supplemental irrigation (Pinheiro et al. 2021). Such adaptation is due to its deep root system, capable of absorbing the available water at greater depths, and thus, ensuring greater tolerance to short periods of water deficit. In addition, its short cultivation cycle reduces the need for irrigation, which makes it a strategic crop for these regions (Tolk and Howell 2012). However, under prolonged drought conditions, the plant has low efficiency in leaf expansion and reduced transpiration rate, which significantly interferes with crop yield (Pekcan et al. 2015; Hussain et al. 2018; Ebrahimian et al. 2019).

Sunflower has moderate salinity tolerance (El-Hameid and Sadak 2020; Li et al. 2020; Ma et al. 2021) and can be grown in soils with a salinity of up to 4.8 dS m^{-1}, without reducing the significant impact on their income (Francois 1996; Katerji et al. 2000). However, salt stress can inhibit their growth in more vulnerable developmental stages, resulting in irreversible physiological damage and decreased productivity (Zeng et al. 2014; Torabian et al. 2016; Jiménez-Becker et al. 2019).

The ability of a crop to survive and grow under saline stress conditions may vary, among other factors, depending on the cultivar used and its growth stage (Li et al. 2020; Wang et al. 2022). Germination is the first stage of plant growth, and crops are more susceptible to salt stress at this stage (Dehnavi et al. 2020). In this sense, the ability to germinate in saline conditions may be an indication of greater tolerance to stress.

Li et al. (2020) carried out a study with seeds of 552 sunflower germplasm subjected to nine concentrations of NaCl (25, 50, 75, 100, 150, 200, 250, 300 and 400 mM), and reported a significant reduction in germination rate and index at concentrations above 300 mM, possibly due to the dysfunction caused in seed metabolism. Salinity can influence germination by altering the water imbibition by the seeds, as the reduction of the osmotic potential caused hinders the absorption of water, and therefore, reduces germination (Bijeh 2012; Safdar et al. 2019). Furthermore, the high amount of salt causes osmotic stress and pseudo-drought, leading to decreased water absorption by plant tissues (Dehnavi et al. 2020). Although most seeds germinated under conditions of up to 300 mM NaCl, Li et al. (2020) observed that seedling growth was strongly affected. At the end of this study, and using fuzzy modeling, Li et al. (2020) concluded that of the 552 evaluated germplasms, 30 lineages were considered highly tolerant to salt, 53 tolerant, 366 moderately tolerant, 80 sensitives, and 23 highly sensitive to salt, showing the great variability that this species can present in relation to its performance under salinity conditions (Machekposhti et al. 2017; Yasmeen et al. 2020).

Plant tolerance to saline stress can be, in most cases, associated with morphological and physiological changes (Munns and Tester 2008), especially in the roots, where ions act directly (Ma et al. 2021). For example, Ma et al. (2017a, b) reported that sunflower plants exposed to salinity tend to allocate a greater amount of photoassimilates in the roots as a way of adapting to stress. On the other hand, salinity can affect the growth dynamics and distribution of the root system in the soil profile, influencing the absorption of water and nutrients (Imada et al. 2015; Ma et al. 2021). Ma et al. (2021) observed a decrease in root penetration in sunflower seedlings subjected to salinity levels; however, a significant increase was observed in the vertical growth of the root system, even under stress conditions, but with the application of nitrogen (N) doses. This was observed after plant anthesis, indicating that N fertilization can attenuate the adverse effects of salinity (Zeng et al. 2016). Other strategies, such as the application of antioxidants (e.g., glutathione) and the use of plant growth-promoting rhizobacteria, can attenuate the harmful effects of salinity in sunflower plants (Yasmeen et al. 2020; El-Hameid and Sadak 2020).

The sunflower stem shows a loss in water content due to the increase in salinity in the irrigation water (Li and Zhang 2019; Han et al. 2022). This result illustrates that the stem of this species may be more sensitive to salt when compared to other parts of the plant, such as the capitulum, which did not lose water due to increased salinity (Han et al. 2022). Adverse effects on plant height, stem diameter, and stomatal conductance (g_s) have also been reported by some authors who have evaluated increasing salinity levels in sunflower cultivation (Machekposhti et al. 2017; Han et al. 2022; Wang et al. 2022). Han et al. (2022) observed that for every 1 dS m^{-1} of irrigation water salinity, the plant height decreased by about 1.6 cm. Wang et al. (2022) reported that the g_s in sunflower leaves decreased with increasing soil salinity. Excessive salinity, in addition to damaging plant cells and influencing plant growth, can inhibit g_s and affect the physiological and ecological activities of cultures (Munns et al. 2006; Wang et al. 2022).

The sunflower salinity threshold varies according to the cultivar and the environmental conditions of the growing area (Han et al. 2022). For example, Francois (1996) reported a threshold of 4.6 dS m^{-1}, with a 5% reduction in the final sunflower yield. On the other hand, Machekposhti et al. (2017), evaluating the response of sunflower irrigated with seawater, found that the salinity threshold was 1.6 dS m^{-1}, with yield reduction ranging from 10 to 14% for each 1 dS m^{-1} increase in soil salinity, for the environmental conditions of Sari, Iran. This result is similar to those reported by Han et al. (2022), who obtained salinity threshold values equal to 1.6, 2.6, and 0.3 dS m^{-1} for the years 2018, 2019, and 2020, respectively. Above these thresholds, the authors observed a decrease in yield variables around 1.5, 2.1, and 3.8% for each 1 dS m^{-1} of soil salinity, over the years studied.

3.3.5 Pigeon Pea (*Cajanus cajan (L.) Mill sp.*)

Pigeon pea (*Cajanus cajan* (L.) Mill sp.) is a legume native to India, considered to be a good source of carbohydrates and proteins, having multiple uses, e.g., in human and livestock, green manure and fuel production (Castillo-Gómez et al. 2016; Benítez et al. 2021). It is the main food legume in South Asia and East Africa, where it has great economic and nutritional importance. In addition to protein and carbohydrates, the culture contains about 1.2% fat and 65% cholesterol-free lipids, and is also a great source of fiber, iron, sulfur, calcium, vitamins, and minerals (Solomon et al. 2017; Buch et al. 2020).

In arid and semiarid regions, pigeon pea is considered an important component in agricultural production systems, due to its adaptation to drought and low fertility soils (Yohane et al. 2020; Mekonen et al. 2021). Its branched and deep root system gives it a high capacity for osmotic adjustment under conditions of low water availability, in addition to enabling the chemical restoration of degraded soils through the solubilization of phosphorus and the biological fixation of atmospheric nitrogen (N), which happens from the symbiosis with *Rhizobium* bacteria, being able to fix up to 200 kg of N ha^{-1} (Yohane et al. 2020; Buch et al. 2020; Salvador et al. 2021).

Pigeon pea has a wide variation in maturity (i.e., extra early, early, medium, and late), which allows it to adapt to different environmental conditions and cropping systems (Choudhary et al. 2011). However, areas with high concentrations of salts in the soil constitute a major problem for its production, since it is considered a crop with high sensitivity to salinity, with a threshold below 1.3 dS m^{-1} (Waheed et al. 2006; Duhan et al. 2018; Choudhary et al. 2018; Garg and Sharma 2019).

Salt stress is one of the environmental problems that most limit the dynamics of growth, development, and productivity of legumes in arid and semiarid regions around the world (Araújo et al. 2015). In a study carried out by Tayyab et al. (2016), the authors reported that plant height, relative growth rate, and fresh and dry pigeon pea biomass were severely reduced with increasing soil salinity levels (ECe 0.5, 1.6, 2.8, 3.5, 3.8, and 4.3 dS m^{-1}) and plant death was observed after 14 weeks of exposure to the highest levels of salt. A decrease in plant biomass in pigeon pea as a function of salinity was also reported by Garg and Sharma (2019), who observed greater effects on the root system than on the shoot, with a decrease in mycorrhizal colonization, and consequently, a reduction in the efficiency of nitrogen fixation, which in turn may be related to higher concentrations of Na^+ in roots and nodules.

In pigeon pea, the salinity response may vary according to the maturation group, where early genotypes are more sensitive than late cycle genotypes (Choudhary et al. 2018). Some studies showed no correlation between germination tolerance and later stages of growth; however, the ability to survive under salt stress showed some association with seed production under these conditions (Choudhary et al. 2011, 2018). Duhan et al. (2018) observed no deleterious effects and no decline in percentage survival in pigeon pea seedlings subjected to a salinity of 30 mM NaCl. On the other hand, the authors reported that the effects were more pronounced when stress was applied at later stages of development. A significant reduction in flower and pod production was reported by Tayyab et al. (2016).

Morphological and biochemical characteristics, as well as molecular responses to salt stress, are expressed differently between sensitive and tolerant genotypes of this crop (Awana et al. 2019). A study by Awana et al. (2020) evaluating two genotypes, ICP1071 (salt sensitive) and ICP7 (salt tolerant), showed that under non-stressful conditions, the physiological pattern of plants was not altered; however, when saline stress was imposed, specific biochemical responses in each genotype were observed, mainly concerning the production of proteins that help in the synthesis of antioxidant enzymes (e.g., cysteine synthase), indicating that the accumulation of these enzymes may contribute to the tolerance of the ICP7 genotype.

In general, there are few reports on the tolerance of pigeon pea to salinity, and considering its socioeconomic importance in various parts of the world, it is necessary to develop studies that address this issue, to provide consistent information that favors proper management of the culture and, consequently, improve its performance under these conditions.

4 Conclusions

In this review, a summary of the consequences of using lower-quality water in irrigated agriculture was presented, focusing on the effects of water salinity on soil and crops. Water quality for irrigation and salinity tolerance of forage plant species with productive potential for semiarid regions were also addressed.

The effects of water and soil salinity are observed during all stages of plant growth and development. The early stage of development (i.e., germination and seedling growth) is the most critical. However, attention is also needed in the other stages of development so that growth and productivity problems do not appear in the crop.

The forage plants reported in this review have salinity tolerance ranging from low to moderate. The management adopted, as well as the species used are factors that influence the performance of the crop under stress. Although they are widely cultivated in arid and semiarid regions of the world, there are still few studies that show the salinity threshold of these crops, mainly for cactus pear, sunflower, and pigeon pea species. Therefore, it is essential to carry out more research on this topic in order to provide information that improves the management of production systems in saline environments around the world.

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Declarations

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References

Ali AYA, Ibrahim MEH, Zhou G et al (2020) Exogenous jasmonic acid and humic increased salinity tolerance of sorghum. Agron J 112(2):971–884. https://doi.org/10.1002/agj2.20072

Alonso MP, Moraes EHBK, Pereira DH et al (2017) Pearl millet grain for beef cattle in crop-livestock integration system: intake and digestibility. Semina: Ciênc Agrár 38(3):1461–1471. https://doi.org/10.5433/1679-0359.2017v38n3p1461

Al-Reyami NS, Shaik F, Lakkimsetty NR (2020) Environmental impact on usage of treated effluents from istp for irrigation. J Water Process Eng 36:101363. https://doi.org/10.1016/j.jwpe.2020.101363

Araújo SS, Beebe S, Crespi M et al (2015) Abiotic stress responses in legumes: strategies used to cope with environmental challenges. Crit Rev Plant Sci 34(1–3):237–280. https://doi.org/10.1080/07352689.2014.898450

Araújo Júnior GN, Silva TGF, Souza LSB et al (2021) Productivity, bromatological composition and economic benefits of using irrigation in the forage cactus under regulated deficit irrigation in a semiarid environment. Bragantia 80:e1221. https://doi.org/10.1590/1678-4499.20200390

Araújo Júnior GN, Silva TGF, Souza LSB et al (2021) Phenophases, morphophysiological indices and cutting time in clone of the forage cacti under controlled water regimes in a semiarid environment. J Arid Environ 190:104510. https://doi.org/10.1016/j.jaridenv.2021.104510

Awana M, Yadav K, Rani K et al (2019) Insights into salt stress-induced biochemical, molecular and epigenetic regulation of spatial responses in pigeonpea (*Cajanus cajan* L.). J Plant Growth Regul 38:1545–2156. https://doi.org/10.1007/s00344-019-09955-4

Awana M, Jain N, Samota MK, Rani K et al (2020) Protein and gene integration analysis through proteome and transcriptome brings new insight into salt stress tolerance in pigeonpea (*Cajanus cajan* L.). Int J Biol Macromol 164:3589–3602. https://doi.org/10.1016/j.ijbiomac.2020.08.223

Ayub MA, Ahmad HR, Ali M et al (2020) Chapter 3 - Salinity and its tolerance strategies in plants. Plant Life Under Changing Environ:47–76. https://doi.org/10.1016/B978-0-12-818204-8.00003-5

Bafeel SO (2014) Physiological parameters of salt tolerance during germination and seedling growth of *Sorghum bicolor* cultivars of the same subtropical origin. Saudi J Biol Sci 21(4):300–304. https://doi.org/10.1016/j.sjbs.2014.05.005

Benítez RB, Tabares WFE, Velásquez LAL et al (2021) Enzymatic hydrolysis as a tool to improve total digestibility and techno-functional properties of pigeon pea (*Cajanus cajan*) starch. Heliyon 7(8):e07817. https://doi.org/10.1016/j.heliyon.2021.e07817

Bergamaschine AF, Freitas RVL, Valério Filho WV et al (2011) Substituição do milho e farelo de algodão pelo milheto no concentrado da dieta de novilhos em confinamento. Rev Bras Zootec 40(1):157–159. https://doi.org/10.1590/S1516-35982011000100022

Bhattarai B, Singh S, West CP et al (2020) Water depletion patter and water use efficiency of forage sorghum, pearl millet, and corn under water limiting condition. Agric Water Manag 238:106206. https://doi.org/10.1016/j.agwat.2020.106206

Bijeh KMH (2012) Studying the effects of different levels of salinity which caused by NaCl on early growth and germination of *Lactuca Sativa* L. seedling. J Stress Physiol Biochem 8(1):203–208

Bortolini L, Maucieri C, Borin M (2018) A tool for the evaluation of irrigation water quality in the arid and semiarid regions. Agronomy 8(2):1–15. https://doi.org/10.3390/agronomy8020023

Buch DU, Sharma OA, Pable AA, Barvkar VT (2020) Characterization of microRNA genes from Pigeonpea (*Cajanus cajan* L.) and understanding their involvement in drought stress. J Biotechnol 321:23–34. https://doi.org/10.1016/j.jbiotec.2020.06.019

Butcher K, Wick AF, Desustter T, Chatterjee A, Harmon J (2016) Soil salinity: a threat to global food security. Agron J 108(6):2189–2200. https://doi.org/10.2134/agronj2016.06.0368

Cakmakci T, Sahin U (2021) Improving silage maize productivity using recycled wastewater under different irrigation methods. Agric Water Manag 255:107051. https://doi.org/10.1016/j.agwat.2021.107051

Cao Y, Tian Y, Gao L, Chen Q (2016) Attenuating the negative effects of irrigation with saline water on cucumber (*Cucumis sativus* L.) by application of straw biological-reactor. Agric Water Manag 163:169–179. https://doi.org/10.1016/j.agwat.2015.09.021

Carabali JQ, García JG, Solano M et al (2019) Evaluación de la calidad de agua para riego y aprovechamiento del recurso hídrico de la quebrada Togllahuyco. Siembra 6(2):46–57. https://doi.org/10.29166/siembra.v6i2.1641

Carvalho AA, Montenegro AAA, Lima JLMP et al (2021) Coupling water resources and agricultural practices for sorghum in a semiarid environment. Water 13(16):1–25. https://doi.org/10.3390/w13162288

Castillo-Gómez C, Narváez-Solarte W, Hahn-Von-Hessberg CM (2016) Agromorfologia y ussos del *Cajanus cajan* L. Millsp. (FABACEA). Bol Cient Centro Museos Museo Hist Nat 20(1):52–62. https://doi.org/10.17151/bccm.2016.20.1.5

Chakravarthi MK, Reddy YR, Rao KS et al (2017) A study on nutritive value and chemical composition of sorghum fodder. Int J Sci Environ Technol 6(1):104–109

Cheng M, Wang H, Fan J et al (2021) Crop yield and water productivity under salty water irrigation: a global meta-analysis. Agric Water Manag 256:107105. https://doi.org/10.1016/j.agwat.2021.107105

Choudhary AK, Sultana R, Pratap A et al (2011) Breeding for abiotic stresses in pigeon pea. J Food Legumes 24(3):165–174

Choudhary AK, Sultana R, Vales MI et al (2018) Integrated physiological and molecular approaches to improvement of abiotic stress tolerance in two pulse crops of the semi-arid tropics The Crop Journal 6(2):99–114. https://doi.org/10.1016/j.cj.2017.11.002

Coelho DS, Simões WL, Salviano AM et al (2018) Gas Exchange and organic solutes in forage sorghum genotypes grown under different salinity levels. Rev Bras Engenharia Agrícola Ambiental 22(4):231–236. https://doi.org/10.1590/1807-1929/agriambi.v22n4p231-236

Cucci G, Lacolla G, Rubino P (2013) Irrigation with saline-sodic water: effects on soil chemical-physical properties. Afr J Agric Res 8(4):358–365. https://doi.org/10.5897/AJAR11.1222

Daliakopoulos IN, Tsanis IK, Koutroulis A et al (2016) The threat of soil salinity: a European scale review. Sci Total Environ 573:727–739. https://doi.org/10.1016/j.scitotenv.2016.08.177

De La Paix MJ, Lanhai L, Asmed CX, Varenyam A (2013) Soil degradation and altered flood risk as a consequence of deforestation. Land Degrad Dev 24:478–485. https://doi.org/10.1002/ldr.1147

Dehnavi AR, Zahedi M, Ludwiczak A et al (2020) Effect of salinity on seed germination and seedling development of Sorghum (*Sorghum bicolor* (L.) Moench) genotypes. Agronomy 10(6):859. https://doi.org/10.3390/agronomy10060859

Deinlein U, Stephan AB, Horie T et al (2014) Plant salt-tolerance mechanisms. Trends Plant Sci 19(6):371–379. https://doi.org/10.1016/j.tplants.2014.02.001

Dias NS, Blanco FF, Souza ER et al (2016) Efeitos dos sais na planta e tolerância das culturas à salinidade. In: Gheyi HR, Dias NS, Lacerda CF, Gomes Filho E (ed) Manejo da salinidade na agricultura: Estudos básicos e aplicados. Fortaleza, p 1–12

Dias-Martins A, Pessanha KLF, Pacheco S et al (2018) Potential use of pearl Millet (*Pennisetum glaucum* (L.) R. Br.) in Brazil: food security, processing, health benefits and nutritional products. Food Res Int 109:175–186. https://doi.org/10.1016/j.foodres.2018.04.023

Diniz WJS, Silva TGF, Ferreira JMS et al (2017) Forage cactus-sorghum intercropping at different irrigation water depths in the Brazilian Semiarid Region. Pesq Agrop Brasileira 52:724–733. https://doi.org/10.1590/S0100-204X2017000900004

Dubeux Júnior JCB, Santos MVF, Cunha MV et al (2021) Cactus (*Opuntia* and *Nopalea*) nutritive value: a review. Anim Feed Sci Technol 275:114890. https://doi.org/10.1016/j.anifeedsci.2021.114890

Duhan S, Kumari A, Bala S, Sharma N, Sheokand S (2018) Effects of waterlogging, salinity and their combination on stress indices and yield attributes in pigeonpea (*Cajanus cajan* (L.) Millsp.) genotypes. Indian J Plant Physiol 23(1):65–76. https://doi.org/10.1007/s40502-018-0352-1

Ebrahimian E, Seyyedi SM, Bybord A, Damalas CA (2019) Seed yield and oil quality of sunflower, safflower, and sesame under different levels of irrigation water availability. Agric Water Manag 218:149–157. https://doi.org/10.1016/j.agwat.2019.03.031

El-Hameid ARA, Sadak MS (2020) Impact of glutathione on enhancing sunflower growth and biochemical aspects and yield to alleviate salinity stress. Biocatal Agric Biotechnol 29

El-Mageed TAA, Rady MOA et al (2021) Consecutive seasonal effect on yield and water productivity of drip deficit irrigated sorghum in saline soils. Saudi J Biol Sci 29(4):2683–2690. https://doi.org/10.1016/j.sjbs.2021.12.045

Elmongy MS, Zhou H, Cao Y et al (2018) The effect of humic acid on endogenous hormone levels and antioxidant enzyme activity during in vitro rooting of evergreen azalea. Sci Hortic (Amsterdam) 227:234–243. https://doi.org/10.1016/j.scienta.2017.09.027

FAO (2022) Food and Agriculture Organization of the United Nations. Global Soil Partnership. Available at: https://www.fao.org/global-soil-partnership/resources/highlights/detail/en/c/1412475/. Accessed 8 Jan 2022

FAOSTAT (2022) Food and Agriculture Organization of the United Nations. Available at: https://www.fao.org/land-water/databases-and-software/cropinformation/sorghum/en/. 30 Jan 2022

Feng G, Zhu C, Wu Q (2021) Evaluating the impacts of saline water irrigation on soil water-salt and summer maize yield in subsurface drainage condition using coupled HYDRUS and EPIC model. Agric Water Manag 258:107175. https://doi.org/10.1016/j.agwat.2021.107175

Francois LE (1996) Salinity effects on four sunflower hybrids. Agron J 88:215–219. https://doi.org/10.2134/agronj1996.00021962008800020016x

Freire JL, Santos MVF, Dubeux Júnior JC et al (2018) Growth of cactos pear cv Miúda under diferente salinity levels and irrigation frequencies. An Acad Bras Ciênc 90(4):3893–3900. https://doi.org/10.1590/0001-3765201820171033

Freire JL, Santos MVF, Dubeux Júnior JCB et al (2021) Evaluation of cactos pear clones subjected to salt stress. Trop Grassl-Forrajes Trop 9(2):235–242. https://doi.org/10.17138/TGFT(9)235-242

Gajender SG, Dagar JC et al (2014) Performance of edible cactus (*Opuntia ficus-indica*) in saline environments. India J Agric Sci 84(4):73–77

García-Nava F, Peña-Valdivia CB, Trejo C et al (2015) Biophysical and physiological characteristics of nopalitos (*Opuntia* spp., *Cactaceae*) as influenced by domestication. Genet Resour Crop Evol 62(6):927–938. https://doi.org/10.1007/s10722-014-0201-7

Garg N, Sharma A (2019) Role of putrescine (Put) in imparting salt tolerance through modulation of put metabolism, mycorrhizal and rhizobial symbioses in *Cajanus cajan* (L.) Mill sp. Symbiosis 79:59–74. https://doi.org/10.1007/s13199-019-00621-7

Gharaibeh MA, Ghezzehei TA, Albalasmeh AA, Alghzawi MZ (2016) Alteration of physical and chemical characteristics of clayey soils by irrigation with treated wastewater. Geoderma 276:33–40. https://doi.org/10.1016/j.geoderma.2016.04.011

Gupta B, Huang B (2014) Mechanism of salinity tolerance in plants: physiological, biochemical, and molecular characterization. Int J Genomics 2014:1–18. https://doi.org/10.1155/2014/701596

Han X, Kang Y, Wan S, Li X (2022) Effect of salinity on oleic sunflower (*Helianthus annuus* Linn.) under drip irrigation in arid area of Northwest China. Agric Water Manag 259:107267. https://doi.org/10.1016/j.agwat.2021.107267

Hassan S, Inglese P, Gristina L et al (2019) Root growth and soil carbon turnover in *Opuntia ficus-indica* as affected by soil volume availability. Eur J Agron 105:104–110. https://doi.org/10.1016/j.eja.2019.02.012

Hussain M, Farooq S, Hasan W et al (2018) Drought stress in sunflower: physiological effects and its management through breeding and agronomic alternatives. Agric Water Manag 201:152–166. https://doi.org/10.1016/j.agwat.2018.01.028

Imada S, Matsuo N, Acharya K, Yamanaka N (2015) Effects of salinity on fine root distribution and whole plant biomass of Tamarix ramosissima cuttings. J Arid Environ 114:84–90. https://doi.org/10.1016/j.jaridenv.2014.11.011

Inglese P, Liguori G, Barrera EDL (2017) Ecophysiology and reproductive biology of cultivated cacti. In: Inglese P, Mondragón C, Nefzaoui A, Sáenz C (eds) Crop Ecology, Cultivation and Uses of Cactus Pear. Food and Agriculture Organization and International Center for Agricultural Research in the Dry Areas, Rome, pp 29–41

Jardim AMRF, Silva GIN, Biesdorf EM et al (2020a) Production potential of *Sorghum bicolor* (L.) Moench crop in the Brazilian semiarid: review. Pubvet 14(4):1–13. https://doi.org/10.31533/pubvet.v14n4a550.1-13

Jardim AMRF, Silva TGF, Souza LSB, Souza MS (2020b) Interaction of agroecosystem intercropped with forage cactus-sorghum in the semiarid environment: a review. J Environ Anal Progress 5(1):69–87. https://doi.org/10.24221/jeap.5.1.2020.2743.069-087

Jardim AMRF, Silva TGF, Souza LSB et al (2021) Intercropping forage cactus and sorghum in a semiarid environment improves biological efficiency and competitive ability through interspecific complementarity. J Arid Environ 188:104464. https://doi.org/10.1016/j.jaridenv.2021.104464

Jha S (2022) Proteome responses of pearl millet genotypes under salinity. Plant Gene 29:100347. https://doi.org/10.1016/j.plgene.2021.100347

Jha S, Singh J, Chouhan C, Singh O, Srivastava RK (2021) Evaluation of multiple salinity tolerance indices for screening and comparative biochemical and molecular analysis of Pearl Millet (*Pennisetum glaucum* (L.) R. Br.) genotypes. J Plant Growth Regul 41:1820–1834. https://doi.org/10.1007/s00344-021-10424-0

Jiménez-Becker S, Ramírez M, Plaza BM (2019) The influence of salinity on the vegetative growth, osmolytes and chloride concentration of four halophytic species. J Plant Nutr 42(15):1838–1849. https://doi.org/10.1080/01904167.2019.1648666

Julkowska MM, Testerink C (2015) Tuning plant signaling and growth to survive salt. Trends Plant Sci 20(9):586–594. https://doi.org/10.1016/j.tplants.2015.06.008

Katerji A, van Hoorn JW, Hamdy A, Mastrorilli M (2000) Salt tolerance classification of crops according to soil salinity and to water stress day index. Agric Water Manag 43(1):99–109. https://doi.org/10.1016/S0378-3774(99)00048-7

Köster P, Wallrad L, Edel KH et al (2018) The battle of two ions Ca^{2+} signaling against Na^{+} stress. Plant Biol 21:39–48. https://doi.org/10.1111/plb.12704

Krishnamurthy L, Serraj R, Hash CT et al (2007) Screening sorghum genotypes for salinity tolerant biomass production. Euphytica 156:15–24. https://doi.org/10.1007/s10681-006-9343-9

Lallouche B, Boutekrabt A, Hadjkouider B et al (2017) Use of physio-biochemical traits to evaluate the salt tolerance of five *Opuntia* species in the Algerian steppes. Pak J Bot 49(3):837–845

Lemos M, Ferreira Neto M, Fernandes CS et al (2021) The effect of domestic sewage effluent and planting density on growth and yield of prickly pear cactus in the semiarid region of Brazil. J Arid Environ 185:104372. https://doi.org/10.1016/j.jaridenv.2020.104372

Li CS, Zhang Z (2019) Effects of ionic components of saline water on irrigated sunflower physiology. Water 11(2):1–12. https://doi.org/10.3390/w11020183

Li W, Zhang H, Zeng Y et al (2020) A salt tolerance evaluation method for sunflower (*Helianthus annuus* L.) at the seed germination stage. Sci Rep 10:10626. https://doi.org/10.1038/s41598-020-67210-3

Li D, Wan S, Li X, Kang Y, Han X (2022) Effect of water-salt regulation drip irrigation with saline water on tomato quality in an arid region. Agric Water Manag 261:107347. https://doi.org/10.1016/j.agwat.2021.107347

Libutti A, Gatta G, Gagliari A et al (2018) Agro-industrial wastewater reuse for irrigation of a vegetable crop succession under Mediterranean conditions. Agric Water Manag 196:1–14. https://doi.org/10.1016/j.agwat.2017.10.015

Lothrop N, Bright KR, Sexton J et al (2018) Optimal strategies for monitoring irrigation water quality. Agric Water Manag 199:86–92. https://doi.org/10.1016/j.agwat.2017.12.018

Ma T, Zeng W, Li Q, Wu J, Huang J (2017a) Effects of water, salt and nitrogen stress on sunflower (*Helianthus annuus L.*) at different growth stages. J Soil Sci Plant Nutr 16:1024–1037. https://doi.org/10.4067/S0718-95162016005000075

Ma T, Zeng W, Li Q (2017b) Shoot and root biomass allocation of sunflower varying with soil salinity and nitrogen applications. Agron J 109:2545–2555. https://doi.org/10.2134/agronj2017.04.0194

Ma T, Zeng W, Lei G, Wu J, Huang J (2021) Predicting the rooting depth, dynamic root distribution and the yield of sunflower under different soil salinity and nitrogen applications. Ind Crop Prod 170:113749. https://doi.org/10.1016/j.indcrop.2021.113749

Maas EV (1986) Salt tolerance of plants. Appl Agric Res 1:12–25

Machekposhti MF, Shahanazari A, Ahmadi MZ et al (2017) Effect of irrigation with sea water on soil salinity and yield of oleic sunflower. Agric Water Manag 188:69–78. https://doi.org/10.1016/j.agwat.2017.04.002

Mahmoud NE, Abdelhameed RM (2021) Superiority of modified graphene oxide for enhancing the growth, yield, and antioxidant potential of pearl millet (*Pennisetum glaucum* L.) under salt stress. Plant Stress 2:1000025. https://doi.org/10.1016/j.stress.2021.100025

Martínez-Alvarez V, Martin-Gorriz B, Soto-García M (2016) Seawater desalination for crop irrigation – a review of current experiences and revealed key issues. Desalination 381:58–70. https://doi.org/10.1016/j.desal.2015.11.032

Mekonen T, Tolera A, Nurfeta A et al (2021) Location and plant spacing affect biomass yield and nutritional value of pigeon pea forage. Agron J 133:1–20. https://doi.org/10.1002/agj2.20803

Minhas PS, Ramos TB, Ben-Gal A, Pereira LS (2020) Coping with salinity in irrigated agriculture: crop evapotranspiration and water management issues. Agric Water Manag 227:105832. https://doi.org/10.1016/j.agwat.2019.105832

Mitharwal S, Kumar S, Chauhan K (2021) Nutritional, polyphenolic composition and in vitro digestibility of finger millet (*Eleusine coracana* L.) with its potential food applications: a review. Food Bioscience 44(Part A):101382. https://doi.org/10.1016/j.fbio.2021.101382

Munns R, Tester M (2008) Mechanisms of salinity tolerance. Annu Rev Plant Biol 59:651–681. https://doi.org/10.1146/annurev.arplant.59.032607.092911

Munns R, James RA, Lauchli A (2006) Approaches to increasing the salt tolerance of wheat and other cereals. J Exp Bot 57(5):1025–1043. https://doi.org/10.1093/jxb/erj100

Negrão S, Schmöckel SM, Tester M (2016) Evaluating physiological responses of plants to salinity stress. Ann Bot 119(1):1–11. https://doi.org/10.1093/aob/mcw191

Nghiem NP, Montanti J, Johnston DB (2016) Sorghum as a renewable feedstock for production of fuels and industrial chemicals. AIMS Bioeng 3(1):75–91

Nikalje GC, Srivastava AK, Pandey GK, Suprasanna P (2017) Halophytes in biosaline agriculture: mechanism, utilization, and value addition. Land Degrad Dev 29:1081–1095. https://doi.org/10.1002/ldr.2819

Nimir NEA, Lu S, Zhou G et al (2014) Exogenous hormones alleviated salinity and temperature stress on germination and early seedling growth of sweet sorghum. Agron J 106(6):2305–2315. https://doi.org/10.2134/agronj13.0594

Nimir NEA, Lu S, Zhou G et al (2015) Comparative effects of gibberellic acid, kinetin and salicylic acid on emergence, seedling growth and the antioxidant defense system of sweet sorghum (*Sorghum bicolor* L.) under salinity and temperature stresses. Crop Pasture Sci 66:145–157. https://doi.org/10.1071/CP14141

Nobel PS, Luttge U, Heuer S, Ball E (1984) Influence of applied NaCl on crassulacean acid metabolism and ionic levels in a cactus, *Cereus-validus*. Plant Physiol 75:799–803. https://doi.org/10.1104/pp.75.3.799

Norton-Brandão D, Scherrenberg SM, Van Lier JB (2013) Reclamation of used urban waters for irrigation purposes – a review of treatment technologies. J Environ Manag 122:85–98. https://doi.org/10.1016/j.jenvman.2013.03.012

Nouri H, Borujeni SC, Nirola R et al (2017) Application of green remediation on soil salinity treatment: review on halophyteremediation. Process Saf Environ Prot 107:94–107. https://doi.org/10.1016/j.psep.2017.01.021

Ochoa Alfaro AE, Kessler MR, Morales MBP et al (2012) Functional characterization of an acidic SK(3) dehydrin isolated from an *Opuntia streptacantha* cDNA library. Planta 235:565–578. https://doi.org/10.1007/s00425-011-1531-8

Pekcan V, Evci G, Yilmaz I et al (2015) Drought effects on yield traits of some sunflower inbred lines. Agric For 61(4):101–107. https://doi.org/10.17707/AgricultForest.61.4.10

Pennells J, Cruickshank A, Chaléat C et al (2021) Sorghum as a novel biomass for the sustainable production of cellulose nanofibers. Ind Crops Prod 171:113917. https://doi.org/10.1016/j.indcrop.2021.113917

Perazzo AF, Santos EM, Pinho RM et al (2013) Características agronômicas e eficiência do uso da chuva em cultivares de sorgo no semiárido. Ciência Rural 43:10. https://doi.org/10.1590/S0103-84782013001000007

Pereira LS, Paredes P, Jovanovic N (2020) Soil water balance models for determining crop water and irrigation requirements and irrigation scheduling focusing on the FAO56 method and the dual K_c approach. Agric Water Manag 241:106357. https://doi.org/10.1016/j.agwat.2020.106357

Perri S, Suweis S, Entekhabi D, Milini A (2018) Vegetation controls on dryland salinity. Geophys Res Lett 45:11669–11682. https://doi.org/10.1029/2018GL079766

Perri S, Suweis S, Holmes A et al (2020) River basin salinization as a form of aridity. PNAS 117(30):17635–17642. https://doi.org/10.1073/pnas.2005925117
Pinheiro AG, Souza LSB, Jardim AMRF et al (2021) Lacunas de produtividade e estratégias de cultivo na melhoria da produção de forragem para a região semiárida brasileira – Revisão. Rev Bras Geogr Fís 14(4):2403–2426. https://doi.org/10.26848/rbgf.v14.4.p2403-2426
Pizarro F (1985) Drenaje agrícola y recuperación de suelos salinos. 2° ed. Madrid: Editora Agricola Espanhola, S.A., pp 542
Pizarro F (1996) Riegos localizados de alta frecuencia (RLAF). goteo, microaspersión y exudación. 3° ed. rev. y amp. Madrid: Mundi-Prensa. pp 513
Porto Filho FQ, Medeiros JF, Gheyi HR et al (2011) Evolução da salinidade e pH de solo sob cultivo de melão irrigado com água salina. Rev Bras Eng Agríc Ambient 15(11):1130–1137. https://doi.org/10.1590/S1415-43662011001100004
Punia H, Bhadu S, Tokas J, Satpal, (2019) Variation in structural carbohydrates of forage sorghum (*Sorghum Bicolor* (L.) Moench) under saline conditions. Forage Res 42(2):123–127
Punia H, Tokas J, Bhadu S, Mohanty AK et al (2020) Proteome dynamics and transcriptome profiling in sorghum [*Sorghum bicolor* (L.) Moench] under salt stress. Biotech 10(9):1–10. https://doi.org/10.1007/s13205-020-02392-1
Punia H, Tokas J, Malik A et al (2021) Discerning morpho-physiological and quality traits contributing to salinity tolerance acquisition in sorghum [*Sorghum bicolor* (L.) Moench]. S Afr J Bot 140:409–418. https://doi.org/10.1016/j.sajb.2020.09.036
Qadir M, Sposito G, Smith CJ, Oster JD (2021) Reassessing irrigation water quality guidelines for sodicity hazard. Agric Water Manag 255:107054. https://doi.org/10.1016/j.agwat.2021.107054
Queiroz MG, Silva TGF, Zolnier S (2015) Características morfofisiológicas e produtividade da palma forrageira em diferentes lâminas de irrigação. Rev Bras Eng Agríc Ambient 19(10):931–938. https://doi.org/10.1590/1807-1929/agriambi.v19n10p931-938
Queiroz MG, Silva TGF, Zolnier S et al (2016) Hydro-economic relations of forage cactus cultivated in semiarid environment. Irriga 1(1):141–154. https://doi.org/10.15809/irriga.2016v1n01p141-154
Rao TSRB, Naresh JV, Reddy PS (2017) Expression of *Pennisetum glaucum* eukariotic translational initiation factor 4A (PgelF4A) confers improved drought, salinity, and oxidative stress tolerance in groundnut. Front Plant Sci 8:45. https://doi.org/10.3389/fpls.2017.00453
Rengasamy P (2006) World salinization with emphasis on Australia. J Exp Bot 57(5):1017–1023. https://doi.org/10.1093/jxb/erj108
Rengasamy P (2010) Soil processes affecting crop production in salt-affected soils. Funct Plant Biol 37(7):613–620. https://doi.org/10.1071/FP09249
Richards LA (1954) Diagnose and improvement of saline and alkali soils. Washington: USDA, pp 60. (Handbook, 60)
Safdar H, Amin A, Shafiq Y et al (2019) A review: impacto of salinity on plant growth. Nat Sci 17(1):34–40. https://doi.org/10.7537/marsnsj170119.06
Salvador KRS, Jardim AMRF, Araújo Júnior GN et al (2021) Intensificação de sistemas de produção de palma forrageira por meio de consorciação rotativa com gramíneas, leguminosas e oleaginosas: uma revisão. Rev Bras Geogr Fís 14(4):2369–2390. https://doi.org/10.26848/rbgf.v14.4.p2322-2343
Samarappuli D, Barti MT (2018) Intercropping forage sorghum with maize is a promising alternative to maize silage for biogas production. J Clean Prod 194:515–524. https://doi.org/10.1016/j.jclepro.2018.05.083
Santos R, Neves AL, Pereira LG et al (2017) Divergence in agronomic traits and performance of pearl millet cultivars in Brazilian semiarid region. Grassland Sci 63:118–127. https://doi.org/10.1111/grs.12154
Scalisi A, Morandi B, Inglese P, Bianco RLO (2016) Cladode growth dynamics in *Opuntia fícus-indica* under drought. Environ Exp Bot 122:158–167. https://doi.org/10.1016/j.envexpbot.2015.10.003
Singh K (2016) Microbial and enzyme activities of saline and sodic soils. Land Degrad Develop 27:706–718. https://doi.org/10.1002/ldr.2385
Singh A (2019) Poor-drainage-induces salinization of agricultural lands: Management through structural measures. Land Use Policy 82:457–463. https://doi.org/10.1016/j.landusepol.2018.12.032
Singh J, Reddy PS, Reddy CS, Reddy MK (2015) Molecular cloning and characterization of salt inducible dehydrin gene from the C4 plant *Pennisetum glaucum*. Plant Gene 4:55–63. https://doi.org/10.1016/j.plgene.2015.08.002
Singh G (2004) An overview of cactus pear research and development in India. In V International Congress on Cactus Pear and Cochineal*,* 728, pp. 43-50
Sinha I, Buttar GS, Brar AS (2017) Drip irrigation and fertigation improve economics, water and energy productivity of spring sunflower (*Helianthus annuus* L.) in Indian Punjab. Agric Water Manag 185:58–64. https://doi.org/10.1016/j.agwat.2017.02.008

Snyman HA (2004) Effect of various water application strategies on root development of *Opuntia ficus-indica* and *O. robusta* under greenhouse growth conditions. J Prof Assoc Cactus Dev 6:35–61
Solomon SG, Okomoda VT, Oda SO (2017) Nutritional value of toasted pigeon pea, *Cajanus cajan* seed and its utilization in the diet of *Clarias gariepinus* (Burchell, 1822) fingerling. Aquac Rep 7:34–39. https://doi.org/10.1016/j.aqrep.2017.05.005
Souza MS, Silva TGF, Souza LSB et al (2019) Practices for the improvement of the agricultural resilience of the forage production in semiarid environment: a review. Amazon J Plant Res 3:417–430. https://doi.org/10.26545/ajpr.2019.b00051x
Souza MS, Silva TGF, Souza LSB et al (2021) Growth, phenology and harvesting time oof cactus-millet intercropping system under biotic mulching. Arch Agron Soil Sci 67:1–15. https://doi.org/10.1080/03650340.2020.1852553
Stamenkovic OS, Siliveru K, Veljkovic VB et al (2020) Production of biofuels from sorghum. Renew Sustain Energy Rev 124:109769. https://doi.org/10.1016/j.rser.2020.109769
Tayyab AM, Qasim M et al (2016) Salt stress responses of pigeon pea (*Cajanus cajan*) on growth, yield and some biochemical attributes. Pak J Bot 48(4):1353–1360
Toderich C, Shuyskaya E, Rakhmankulova Z et al (2018) Threshold tolerance of new genotypes of *Pennisetum glaucum* (L.) R. Br. to salinity and drought. Agronomy 8(10):1–13. https://doi.org/10.3390/agronomy8100230
Tolk JA, Howell TA (2012) Sunflower water productivity in four Great Plains soils. Field Crop Res 127:120–128. https://doi.org/10.1016/j.fcr.2011.11.012
Torabian S, Zahedi M, Khoshgoftar AH (2016) Effects of foliar spray of two kinds of zinc oxide on the growth and ion concentration of sunflower cultivars under salt stress. J Plant Nutr 39(2):172–180. https://doi.org/10.1080/01904167.2015.1009107
Tripathy MK, Tiwari BS, Reddy MK (2017) Ectopic expression of PgRab7 in rice plants (*Oryza sativa* L.) results in differential tolerance at the vegetative and seed setting stage during salinity and drought stress. Protoplasma 254:109–124. https://doi.org/10.1007/s00709-015-0914-2
Uddin MS, Jahan N et al (2017) Growth and yield response of wheat genotypes to salinity at diferent growth stages. Int J Agronomy Agric Res 11(2):60–67
Waheed A, Hafiz IA, Qadir G et al (2006) Effect of Salinity on germination, growth, yield, ionic balance and solute composition of pigeon pea (*Cajanus cajan* (L.) Millsp.). Pak J Bot 38(3):1103–1117
Wang W, Rong Y, Wang X et al (2022) Estimating sunflower canopy conductance under the influence of soil salinity. Agric For Meteorol 314:108778. https://doi.org/10.1016/j.agrformet.2021.108778
Westcot DW, Ayers RS (1985) Irrigation water quality criteria. In: Pettygrove GS, Asano T (eds) Irrigation with reclaimed municipal wastewater – A guidance manual. Lewis Publishers Inc, Chelsea, p 186
Wilson ML, Vanburen R (2022) Leveraging millets for developing climate resilient agriculture. Curr Opin Biotechnol 75:102683. https://doi.org/10.1016/j.copbio.2022.102683
Yadav T, Kumar A, Yadav RK et al (2020) (2017) Salicylic acid and thiourea mitigate the salinity and drought stress on physiological traits governing yield in pearl millet-wheat. Saudi J Biol Sci 27(8):2010–2017. https://doi.org/10.1016/j.sjbs.2020.06.030
Yasmeen T, Ahmad A, Arif MS et al (2020) Biofilm forming rhizobacteria enhance growth and salt tolerance in sunflower plants by stimulating antioxidant enzymes activity. Plant Physiol Biochem 156:242–256. https://doi.org/10.1016/j.plaphy.2020.09.016
Yasuor H, Tamir G, Stein A et al (2017) Does water salinity affect pepper plant response to nitrogen fertigation? Agric Water Manag 191:57–66. https://doi.org/10.1016/j.agwat.2017.05.012
Yasuor H, Yermiyahu U, Ben-Gal A (2020) Consequences of irrigation and fertigation of vegetable crops with variable quality water: Israel as a case study. Agric Water Manag 242:106362. https://doi.org/10.1016/j.agwat.2020.106362
Yin X, Feng Q, Li Y et al (2022) An interplay of soil salinization and groundwater degradation threatening coexistence of oasis-desert ecosystems. Sci Total Environ 806(Part 2):150599. https://doi.org/10.1016/j.scitotenv.2021.150599
Yohane EN, Shimelis H, Laing M, Mathew I, Shayanowako A (2020) Phenotypic divergence analysis in Pigeonpea [*Cajanus cajan* (L.) Millspaugh]. Agronomy 10(11):1682. https://doi.org/10.3390/agronomy10111682
Yousaf L, Hou D, Liaqat H, Shen Q (2021) Millet: a review of its nutritional and functional changes during processing. Food Res Int 142:110197. https://doi.org/10.1016/j.foodres.2021.110197
Zaman M, Shahid SA, Heng L (2018) Irrigation Water Quality. In: Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques. Springer, Cham, p 113–131. https://doi.org/10.1007/978-3-319-96190-3_5

Zeng WZ, Wu JW, Huang JS et al (2014) Impacts of salinity and nitrogen on the photosynthetic rate and growth of sunflowers (*Helianthus annuus* L.). Pedosphere 24(5):635–644. https://doi.org/10.1016/S1002-0160(14)60049-7

Zeng W, Xu C, Wu J, Huang J (2016) Sunflower seed yield estimation under the interaction of soil salinity and nitrogen application. Field Crop Res 198:1–15. https://doi.org/10.1016/j.fcr.2016.08.007

Zörb C, Gelifus CM, Dietz KJ (2018) Salinity and crop yield. Plant Biol 21:31–38. https://doi.org/10.1111/plb.12884

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