

Sustainable soybean production and abiotic stress management in saline environments: a critical review

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Abstract

Soybean (*Glycine max* L.) is an important oilseed crop around the world. Soybean growth, development and productivity are affected by changing environments that induce abiotic stresses. In soybean, salinity acts as a major abiotic stress that increases electrolyte leakage as well as Na⁺ and proline content in plants, and adversely affects plant physiology. This review offers an understanding of how the growth, yield attributes, and yield of soybean decrease under salinity stress. To appreciate how soybean can better adapt to a changing climate that induces salinity stress, an understanding of the mechanisms underlying this stress is needed. Improved performance and yield in response to salinity stress can emerge from the application of novel strategies, such as the development of transgenic crops that enhance salt tolerance in soybean. Effective management strategies, including the use of compatible antioxidants such as proline or glycinebetaine, coupled with a more effective balance of nutrients or the use of organic fertilizers, allow salinity to be mitigated, thereby improving yield and other growth-related quality parameters in soybean.

Keywords: Growth, yield, salinity, soybean, proline, glycinebetaine, compost.

Abbreviations: Ca²⁺_calcium; CAT_catalase; Cl_chloride; chl_chlorophyll; DAO_diamine oxidase; DW_dry weight; EC_electrical conductivity; FW_fresh weight; GB_glycine betaine; HC_hydraulic conductivity; K⁺_potassium; MDA_malondialdehyde; Mg²⁺_magnesium; MGT_mean germination time; N_nitrogen; Na⁺_sodium; P_phosphorus; PEG_polyethylene glycol; Pro_proline; RLWC_relative leaf water content; SOD_superoxide dismutase; SPAD_value_indicates the chlorophyll content and crop colour; WHC_water holding capacity.

Introduction:

Soybean production in an increasingly saline world

Soybean (*Glycine max* L.) is a leguminous plant that is grown for its edible oil and forage with the USA and Brazil being the leading global producers (Vagadia et al., 2017). Soybeans, including processed soybean products such as *tofu*, have good nutritional quality for adult humans, including a high content of proteins (40-50%), lipids (20-30%) and carbohydrates (26-30%), with more than 85% of proteins consisting of β-conglycinin and glycinin (Gibbs et al., 2004). The USDA reports much lower levels of protein (13%), lipids (6.8%), carbohydrates (11%) and dietary fiber (4%) in green raw soybeans (USDA, 2018a), but higher levels in mature raw seeds (36.5%, 20%, 30%, and 9%, respectively) (USDA,

2018b). Soybean also has an abundance of essential fatty acids, including saturated, monounsaturated and polyunsaturated fatty acids (USDA, 2018a, 2018b), and contains beneficial secondary metabolites such as isoflavones, phenolic components and saponins (Sakthivelu et al., 2008). Soybean, which is a good source of low-cost protein and other nutritive factors for humans as well as poultry feed, is a valuable crop for developed and developing nations (Khojely et al., 2018). Agronomic management of production practices, including optimized growth strategies, nutrient fertilizer (Mannan, 2014) and careful selection of genotypes all influence soybean yield (Matsuo et al., 2016; Gulluoglu et al., 2017). Despite this, soybean also contains anti-nutritional compounds such as trypsin inhibitors that need to be eliminated for safe human

consumption (Vagadia et al., 2017). In addition, the increasing use of transgenic GMO soybean, such as herbicide-tolerant soybean, needs careful monitoring and screening to test for safe human consumption (Herman et al., 2018). This issue is important since transgenic salt-tolerant soybean is already in production (Liu et al., 2016), so its safety needs to be carefully evaluated.

Salinity, an abiotic stress, negatively impacts about 20% of 310 million ha of irrigated lands used for crop production, causing an estimated annual loss of US\$ 27 billion (Qadir et al., 2014). Salinity, as the result of a complex accumulation of micro-stress on different cellular components (Zhu, 2016), adversely affects almost all growth stages of leguminous crops, including germination, seedling establishment and vegetative and reproductive stages, especially when applied as diluted seawater during irrigation (Mansouri and Kheloufi, 2017). Salinity also reduces nodulation in soybean, thus affecting nitrogen fixation efficiency, and ultimately yield (Dong et al., 2013). Salinity ultimately decreases the grain yield of leguminous crops (Araújo et al., 2015). However, this negative impact of salinity can be alleviated by applying plant growth-promoting bacteria (Pérez-Montañón et al., 2014; Shrivastava and Kumar, 2015). High soil salinity makes water unavailable and negatively impacts crop growth (for example, it alters metabolic processes, induces nutritional disorders, ion toxicity, and oxidative stress, disturbs the activity of enzymes, disorganizes cell membranes, reduces cell expansion and division), and has a whole host of other biochemical and physiological effects (Hanin et al., 2016; Shu et al., 2017).

Closely related to salinity stress, drought stress also negatively impacts soybean productivity (El Sabagh et al., 2018). This review examines how salinity affects the morphology, biochemistry and physiology of soybean, negatively impacting growth and productivity, and looks to find practical solutions, in the form of antioxidants (e.g., proline (Pro) or glycine betaine (GB)) as well as organic compost, to alleviate this abiotic stress when this crop is cultured in saline soil that would allow for sustainable production.

1. Adverse effect of salinity stress on sustainable soybean production

1.1. Effect of salinity stress on germination and seedling growth of soybean

NaCl-induced salinity stress has an adverse effect on soybean seed germination, seedlings and stand establishment, and stressed seeds tend to show an increase in the production of malondialdehyde (MDA), as well as an increase in the activity of antioxidant enzymes (catalase (CAT), superoxide dismutase (SOD), and peroxidase (POX)), thereby reducing the negative impact on germination and post-germination growth stages (Shu et al., 2017). Shu et al. (2017) found that 150 mM NaCl decreased germination, seedling fresh weight (FW) and radicle length. Khajeh-Hosseini et al. (2002) considered the soybean seedling stage to be more sensitive to salt stress than germination, the latter decreasing above 330 mM and causing mean germination time (MGT) to increase. In contrast, Kargar and Kareh (2017) found that soybean was more resistance to salinity during germination than in the seedling phase across 12 cultivars, and 60 mM of salinity improved radicle growth

and vigor, but decreased plumule growth. Essa (2002) and Hashem et al. (2016) also found that the germination of soybean decreased as salinity level increased.

Under NaCl-induced salinity stress, mainly at 12 and 16 dS m⁻¹, sodium (Na⁺) and chloride (Cl⁻) increased significantly while potassium (K⁺), calcium (Ca²⁺) and magnesium (Mg²⁺) showed a significant reduction in soybean leaves, leading to reduced germination, seedling FW and growth, and seedling K⁺ percentage on a dry weight (DW) basis, ultimately leading to an increase in MGT (Farhoudi et al., 2015). Germination was completely inhibited when NaCl or Na₂SO₄ exceeded 0.3 M, or reduced to 30% or 15%, respectively at 0.3 M, down from 90% in the control, while seedling growth was even more sensitive, showing suppressed growth when NaCl or Na₂SO₄ concentration exceeded 0.2 M (Kumar, 2017). Among 16 soybean cultivars, around 50% showed reduced germination at 75 or 125 mM NaCl while the remainder showed stable or even higher germination, without suffering a reuction in MGT; in contrast, invariably all genotypes showed reduced seedling length and FW, and shorter roots (Putri et al., 2017).

Inhibited soybean seedling growth induced by salinity occurs as a result of limited water uptake caused by a reduction in hydrolysis and translocation of nutrient reserves, thereby reducing seedling vigor (Parveen et al., 2016). Salinity, generally between 7 and 14 dS m⁻¹, reduced root and shoot length and DW, and seedling height and DW, and shoots were affected more adversely than roots, although among 15 genotypes studied, at least two showed salinity tolerance, with higher growth-related values than other genotypes, even at 14 dS m⁻¹ (Agarwal et al., 2015). Salt influenced the onset and rate of germination more in salt-sensitive soybean genotypes than in salt-tolerant ones (Abel and MacKenzie, 1964). Increased Na⁺ uptake reduces seed germination rate and seedling FW (Munns, 2002). Khan et al. (2013) found that plant height, root volume, and leaf SPAD value were affected less than leaf number, leaf area and leaf FW under salinity stress (100 and 150 mM NaCl), and that leaf-related characters such as leaf area, and shoot DW, were more sensitive than root DW at 150 mM NaCl.

Salt stress reduces the absorption of water by accumulating Na⁺ and Cl⁻, leading to an imbalance in the uptake of nutrients (Kumar, 2017). Khajeh-Hosseini et al. (2005) noted that the use of paper towels buffered the negative impact of salinity (50-100 mM NaCl) on soybean seedling growth relative to hydroponics. Taffouo et al. (2009) found that soybean germination was affected by 3 g L⁻¹ of NaCl, with critical thresholds at 9-12 g L⁻¹, reducing leaf Pro content. Salinity stress caused by 25 and 50 mM NaCl reduced seed germination and seedling growth (El Sabagh et al., 2015c).

2.2. Salinity stress affects soybean plant growth, and morphological, physiological and biochemical processes

Salt stress alters the morphological, physiological and biochemical performance of soybean plants, reducing plant height and FW by 30-76% when NaCl was applied at 50-200 mM (Amirjani, 2010). In common bean, salinity most negatively impacts photosynthesis and the photosynthetic apparatus by inducing stomatal closure thereby reducing intercellular CO₂ concentration (Kaymakanova and Stoeva, 2008). The degree of salt tolerance in soybean may depend on genotype and developmental stage. In most studies, a

genotype-dependent response to salinity was clear, but a study by Mannan et al. (2013a) showed a fairly consistent response for 11 salt-tolerant and salt-sensitive cultivars initially selected from a pool of 170 cultivars (Mannan et al., 2010, 2012), where 50 or 100 mM NaCl reduced all vegetative characteristics, namely plant height, leaf, stem, shoot and root DW. Earlier trials by the same group on two cultivars showed that these two concentrations of NaCl significantly increased Pro accumulation but significantly reduced water uptake capacity and the content of chlorophyll (chl) (*a*, *b*, total) (Mannan et al., 2009).

Kao et al. (2006) found that plants of two wild soybean species, *G. soja* and *G. tabacina*, treated with 17, 51 and 85 mM NaCl showed a rapid reduction in leaf area, a response that another wild species, *G. tomentella*, only displayed at 85 mM. Curiously, in the same study, *G. tabacina* showed an increase in root biomass, even at 85 mM, while shoot biomass, photosaturated photosynthetic rate and stomatal conductance decreased in all three species from 17 mM and above.

Salt stress suppresses leaf growth, eventually decreasing photosynthetic area and DW production as a result of a decrease in the permeability of the plasma membrane (Mansour and Salama, 2004). Dolatabadian et al. (2011) found that 25, 50 and 100 mM NaCl decreased shoot and root DW and FW significantly, while plant height was only negatively impacted at 50 mM and above, and leaf number was reduced only at 100 mM. In the same study, leaf area was not affected by salinity, but while cuticle and xylem thickness increased as salinity increased, cortex zone thickness decreased.

All six soybean cultivars tested by Essa and Al-Ani (2001) showed a decrease in plant height, shoot and root DW and chl *a* and *b* content as electrical conductivity increased from 2 to 10 d Sm⁻¹, but the authors failed to describe the results for control (i.e., unstressed) treatments. Su and Bai (2008) found that salinity caused by 100 mM NaCl reduced leaf FW and DW, increased the level of Pro and spermine, and the activity of diamine oxidase, but decreased the levels of putrescine and spermidine. Amirjani (2010) noted a significant increase in Na⁺ content at 100 and 200 mM NaCl-induced salinity while the content of K⁺, Ca²⁺, and Mg²⁺, and the activity of SOD, CAT and POX decreased significantly. In contrast, Shu et al. (2017) only found an increase in POD activity when 150 mM NaCl was used, but only after 72 h of exposure, while SOD and CAT activity and MDA levels remained unchanged, but were generally significantly higher than the control.

Parveen et al. (2016) found that in response to NaCl-induced salinity of 6 and 12 d Sm⁻¹, that the use of salt-resistant soybean genotypes could reverse or improve negative responses caused by salinity, such as reduced leaf area, chl content, membrane stability index, relative water content and the activity of SOD, while salt-sensitive genotypes showed no improvement in these parameters. Wu et al. (2014) found that two wild soybean species, even at 300 mM NaCl, maintained a high water potential and relative water content (RWC), but accumulated less Pro and GB while maintaining a higher K⁺/Na⁺ ratio. El Sabagh et al. (2015b) noted an increase in electrolyte leakage, and Na⁺ and Pro content under salinity stress (10 mM NaCl), but a significant reduction in chl content, nodule number, K⁺, N and RWC in leaves. Salt stress caused by 25 and 50 mM NaCl

reduced plant growth, dry weight, and K⁺ and chl content while Pro content increased (El Sabagh et al., 2015c).

2.3. Seed yield of soybean is affected by salinity stress

NaCl-induced salinity at 3, 6 and 9 d Sm⁻¹ significantly decreased grain FW (i.e., yield), number of pods and grains plant⁻¹ as well as mean grain FW and grain yield plant⁻¹ of three soybean cultivars (Ghassemi-Golezani et al., 2009). Hamayun et al. (2010a) also noted a significant decrease in shoot length, shoot and root DW, chl content, number of pods plant⁻¹, 100-seed weight and yield (g plant⁻¹) in a single soybean cultivar in response to 70 and 140 mM NaCl. The agronomic traits of soybean are generally severely affected by high salinity, as expressed by a reduction in plant height, leaf size, biomass, number of internodes, number of branches, number of pods, weight plant⁻¹, and 100-seed weight (Phang et al., 2008).

Soybean grain yield decreased by about 20% when salinity was 4.0 dS m⁻¹ and by about 56% at 6.7 dS m⁻¹ (Katerji et al., 2003). Reduced crop productivity at high salinity is usually caused by an imbalance of ions, causing toxicity, or due to osmotic stress (Ashraf, 2009). Salinity stress delayed flowering and enhanced pod maturity in soybean, i.e., shortened the period of maturity and pod development, ultimately affecting grain development causing grains to shrivel (Ghassemi-Golezani et al., 2009; Mannan et al., 2013a). This response was consistent for salt-tolerant and salt-sensitive cultivars in the flowering and reproductive and grain-filling stages, with significantly fewer pods plant⁻¹ and pod wall DW yielding lower grain yield (grain plant⁻¹) (Mannan et al., 2013a, 2013b). The negative effect of salinity stress on yield traits and quality are mainly due to the short duration of protein and oil accumulation and reduced seed yield plant⁻¹ (El Sabagh et al., 2015a, 2015b).

2. Management of salinity stress by the exogenous application of compatible antioxidants and soil application of organic fertilizers

Sustainable soybean productivity under salinity conditions needs the development of salt-tolerant varieties as well as appropriate site-specific production technology and management. Soybean cultivars that are tolerant to salt stress and other abiotic stresses may be developed by biotechnology and molecular breeding to generate transgenic cultivars or lines. Practical solutions, such as the exogenous application of osmoprotectants, plant growth regulators, or optimized nutrient content may be cost-effective alternatives to increase soybean productivity under a saline environment. For example, the application of silicon at 100 or 200 mg L⁻¹ reversed or even improved the negative impacts of NaCl and polyethylene glycol (PEG) on soybean growth, such as shoot length, shoot and root FW and DW, and chl content (Hamayun et al., 2010b).

To survive salinity stress, exogenous application of Pro or GB is a simple and practical strategy to improve salinity tolerance in plants (Thapa et al., 2011). Phenolic compounds like Pro and GB act as a compatible solute and antioxidant during stress, and application of Pro helps to mitigate the adverse effects on plants under abiotic stresses while GB protects the thylakoid membrane through osmotic adjustment, thereby maintaining the efficiency of

photosynthesis (Ashraf and Harris, 2004; Ashraf and Foolad, 2007). Pro, an osmoprotectant that also serves as an antioxidant, can mitigate salt stress in plants when applied exogenously. Foliar application of Pro during salt stress increases the survival of plants by protecting protein structure and membranes from injury and decreasing the denaturation of enzymes, i.e., as an antioxidative defense molecule (Ashraf and Foolad, 2007). Pro also serves as a metal chelator and as a signaling molecule by acting as an osmolyte in abiotic stress (Hayat et al., 2012).

2.1. Breeding approaches to mitigate salinity stress in soybean

Soybean is considered as a salt-tolerant crop, but the extent of tolerance depends on both genotype and the environment, and their interaction (Ghassemi Golezani et al., 2009; Mannan et al., 2012, 2013a). The development of salt-tolerant genotypes via selection of suitable genotypes under salinity stress, as well as the implementation of suitable management technologies, are essential for sustaining crop productivity under saline conditions, especially when traditional breeding and biotechnology are combined, e.g., the production of transgenic soybean cultivars with improved salt and abiotic stress tolerance (Fita et al., 2015; Nongpiur et al., 2016).

Genetic improvement of salt tolerance is another effective strategy for sustainable soybean production under salinity stress. The first step in the development of salt-tolerant soybean cultivars is to identify quantitative trait loci (QTL) for salt tolerance whose genes can then be identified by QTL map-based cloning and whole-genome-sequencing approaches that are then applied to marker-assisted selection in soybean breeding programs (Lee et al., 2004; Hamwieh and Xu, 2008; Chen et al., 2008; Hamwieh et al., 2011). Transgenic approaches to increasing oleic acid content (Zhang et al., 2014) or resistance to pests (Marques et al., 2018) already exist. In fact, one such gene *Ncl* was isolated and cloned, and transgenic soybean plants showed greater yield under saline conditions (Do et al., 2016). Iron deficiency in soybean due to high soil pH is responsible for sodic tolerance (Charlson et al., 2005). Several QTLs are associated with sodic tolerance. Tuyen et al. (2010, 2013) identified several wild soybean (*G. soja*) accessions with high sodic tolerance. Apart from increased yield shown by transgenic soybean under saline conditions by Do et al. (2016), Zhang et al. (2013) found that the transgenic expression of a rice transcription factor improved plant growth under saline conditions (200 and 300 mM NaCl) while Guan et al. (2014) found that the *GmSALT3* gene limits the accumulation of Na⁺, and thereby has the ability to improve salinity tolerance. More details about genetic studies related to salinity tolerance may be found in Xu and Tuyen (2012).

2.2. Seed priming to manage salinity

Seed priming is an approach to mitigate abiotic stresses in crops when combined with physiological approaches or genetic engineering. Seed priming is an easy, low-cost and low-risk management strategy that can be effectively and practically used to enhance uniform emergence, high seedling vigor, and improved yield of field crops, including

soybean, under adverse environmental conditions (Ashraf and Foolad, 2005; Paparella et al., 2015).

Priming soybean seed with PEG-8000 to an osmotic potential of -1.1 MPa improved seedling emergence and yield (Arif et al., 2008). Similarly, the use of PEG-6000 for 12 h at an MPa of -1.2 improved several germination indices, including germination percentage, MGT, seed vigor and seed electrical conductivity (Sadeghi et al., 2011). Saeed et al. (2017) found that among several techniques, including three forms of priming, that hydropriming resulted in most rapid seedling emergence, significantly improved plant density, plant height, number of pods plant⁻¹, 1000-seed weight, biological yield and seed yield. Seed priming using KH₂PO₄ or KNO₃ increased mean emergence time, number of pods plant⁻¹ and grain yield plant⁻¹ but had no impact on 1000-grain yield or harvest index (Ghassemi-Golezani et al., 2011). Moshtaghi-Khavarani et al. (2015) used four classes of soybean seeds and hydroprimed them with distilled water or haloprimed them with 75 mM NaCl, finding that the latter improved the germination of large seeds more than small seeds. Sibande et al. (2015) found that priming of soybean seed via hydropriming and the use of plant-based extracts reduced germination and other seedling-related vigour traits and was unable to recover low levels of germination caused by the use of old (two-year-old) seeds. Hydropriming soybean seeds for 12 h or hormonal priming with 50 mg L⁻¹ gibberellic acid (GA₃) for 14 h increased number of pods, grain weight, biological yield and seed yield by promoting early emergence and improving germination (Langeroodi and Noora, 2017). Dai et al. (2017) noted better growth of soybean seedlings and stand establishment as a result of stronger osmotic adjustment, higher activities of antioxidant enzymes (SOD, CAT), increased content of photosynthetic pigments (chl, carotenoids), fortified membrane integrity and a higher accumulation of starch under saline-alkali stress as a result of priming seed by hydropriming (distilled water) and comprehensive seed priming (0.025% ZnSO₄·7H₂O, 52.5 mM CaCl₂·2H₂O, 0.5 g L⁻¹ betaine hydrochloride and 30 mg L⁻¹ GA₃).

3.3. Exogenous application of osmoprotectants under salinity stress

Exogenous application of osmoprotectants or growth regulators, with or without nutrient management, might improve soybean production under a saline-stressed environment.

Glutathione (GSH), which forms part of the plant's detoxification system, and is involved in the detoxification of ROS, when applied at 50 mM at the reproductive stage during salinity stress (50 mM NaCl), improved plant growth, in particular yield plant⁻¹, number of seeds plant⁻¹ and number of pods plant⁻¹ (Akram et al., 2017). Malekzadeh (2015) primed soybean seeds with 50 mM GB for 24 h, after which seedlings were grown under salt stress (150 mM NaCl) showed a decrease in Pro, MDA and Na⁺ content and an increase in CAT and SOD activity. Rezaei et al. (2012) found that foliar application of GB (10 kg ha⁻¹) under salinity (11.1 dS m⁻¹) positively influenced vegetative (number of lateral branches and pods plant⁻¹) and reproductive (1000-grain weight) stages in soybean plants, ultimately increase grain yield.

3.4. Management of salinity stress by application of organic amendments to soil

The application of organic matter such as compost can restore degraded soils, improve biological functions, increase organic carbon, and increase soil physical fertility (Diacono and Montemurro, 2010). Such treatments alone might not however, be able to alleviate the negative impacts of salinity stress.

Hashi et al. (2015) found that the application of K in the form of muriate of potash alleviated the negative impacts caused by salinity of 5.0 or 7.5 dS m⁻¹ induced by watering plants with diluted seawater, thereby improving plant height and leaf and stem dry weight. Parveen et al. (2015) noted that the application of 50 or 75 kg ha⁻¹ improved salt (NaCl)-stressed plant growth, biomass, protein and oil content, all of which decreased when salinity was 6 and 12 dS m⁻¹. The application of farmyard manure as an organic fertilizer improved fatty acid content (linoleic and linolenic acids) more than control and chemical fertilizers, but the effect was not assessed under salinity stress (Mohammadi, 2015). The physical, chemical and biological characteristics of saline soil are significantly improved by adding organic manure, ultimately improving crop growth (Wong et al., 2009). The application of compost (25 t ha⁻¹) to soil combined with a foliar application of osmoprotectants (Pro and GB) increased 100-seed weight, number of pods plant⁻¹ and grain yield of soybean and control and salt-stressed (15 mM NaCl) conditions (El Sabagh et al., 2015a). Enhanced salt tolerance in soybean resulted from the accumulation of Pro, GB, a slight increase in K⁺, and a slight decrease in electrolyte leakage ratio and Na⁺ content (El Sabagh et al., 2015c).

3.5. Management of salinity stress through AMF

Arbuscular mycorrhizal fungi (AMF) are colonizing halophytes that assist the survival of plants under salt stress by improving the physiological and biochemical activity of host plants by increasing root hydraulic conductivity by adjusting the osmotic balance and composition of carbohydrates (Evelin et al., 2009). This has been well established in soybean, as reviewed by Meena et al. (2018). Soybean seeds under saline stress (100 mM NaCl), when inoculated with an AMF (*Glomus etunicatum*), resulted in improved growth of plants, showing an increase in root and shoot FW and DW, root Pro, P, K, and Zn content, but a decrease in shoot Pro and Na⁺ content (Sharifi et al., 2007). The leaf soluble sugar and protein content (Rahmawati et al., 2013) as well as chl *a*, *b* and total chl content increased when an AMF (five indigenous *Glomus* spp.) was inoculated to saline soil, even more so when ascorbic acid was co-applied at 500 mg L⁻¹ (Rahmawati et al., 2014). Younesi et al. (2013) found that the inoculation of soybean with AMF (*Glomus mosseae*) rhizobia enhanced salt stress tolerance (6 and 12 dS m⁻¹) by improving plant growth, nodulation and nitrogen fixation. AMF (three *Glomus* spp.) applied to salt-stressed (200 mM) soil improved almost all growth parameters, as well as the nodulation and nitrogenase content of two soybean cultivars, even more so under non-stressed conditions (Hashem et al., 2016).

3.6. Management of salinity stress through nano-fertilizers

Nanotechnology is being increasingly applied to agriculture, for example as nanofertilizer (Cheng et al., 2016). A nano-iron chelate improved soybean grain oil yield, especially if combined with organic manure (Mohammadi, 2015). Application of nano-SiO₂ enhanced soybean growth and increased germination while a mixture of nano-SiO₂ and nano-TiO₂ significantly increased the nitrate reductase, SOD, CAT and POX activity of germinating seeds in saline stress (Lu et al., 2002). Farhangi-Abri and Torabian (2018) also noted that the application of 0.5 or 1 mM of nano-SiO₂ enhanced soybean seedling shoot and root growth under salt stress (5 and 10 dS m⁻¹) while foliar application of 2 mM hindered growth.

Synthetically synthesized nano-sized hydroxyapatite to deliver P increased the growth and yield of soybean by 33% and 20%, respectively, relative to solid P fertilizers, but the effect in saline soil was not tested (Liu and Lal, 2014). The application of nano cattle manure at 20 t ha⁻¹ significantly improved 1000-grain weight, number of pods plant⁻¹, plant height, grain yield and botanical yield (Aryanpour et al., 2017).

4. Summary, conclusion and future prospect

This review confirms what is widely known, i.e., that salt (or salinity) stress negatively influence soybean plant growth parameters at all growth stages, and a range of morphological, physiological and biochemical processes. Salinity can be managed in soybean by applying osmoprotectants (Pro, GB, GSH), organic manure or even nano-fertilizer, either to sustain growth and yield under salt stress, or to improve them. Transgenic soybean that is tolerant to saline conditions exists, but such biotechnology may be out of reach of many researchers or farmers, so practical solutions that are integrated into an agronomic program, and that incorporate organic amendments into soil, or the foliar application of antioxidants with or without organic fertilizer (El Sabagh et al., 2015d), may improve soybean yield under salinity stress.

Disclaimer statement

We hereby declare the findings of the present review submitted to "AJCS" have been approved by all co-authors who have seen and approved the final version of the manuscript. The manuscript has not been submitted elsewhere nor is it being considered for publication elsewhere. We also declare that this manuscript contains no material which has been accepted for the award of any degree or diploma in any university, and that, to the best of our knowledge and belief, the manuscript contains no copy of any material previously published or written by another person except where due reference is made in the text.

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