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Multifarious Role of Osmolytes in Plants: Signaling and Defense

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Abstract

Abiotic factors are critical ecological issues that limit the development of plants, efficiency, and lifespan and endanger the world's supply of nutrition. Plants synthesize osmolytes, suitable solutes that help them adjust to their continually shifting environment. Osmolytes support the upholding of homeostasis, offer the change in gradient that drives water regulation, retain cell rigidity by means of osmotic adjustment and redox metabolic processes to reduce unnecessary levels of reactive oxygen species, also known as ROS, and restore the cellular redox balance, as well as guard against stress caused by osmotic pressure and damage from oxidative stress to the cells and their machinery. For crop improvement projects to produce stress-tolerant cultivars, it is critical to understand the mechanisms by which plants receive environmental signals and send them to cellular machinery to trigger adaptive responses. Osmolytes build up in plants and have been strongly linked to abiotic stress tolerance, according to a significant number of researches undertaken in the previous few decades. Tolerance in many plant species depends on the production of large amounts of osmolytes. Furthermore, transgenic plants that overexpressed genes for several osmolytes demonstrated improved resistance to a range of abiotic stressors. Particularly in regards to the significance and relative contribution of particular osmolytes to the stress tolerance of a given species, many significant aspects of their mechanisms of action remain to be largely established. Therefore, more time and money should be devoted to researching how plants respond to abiotic stress in their natural environments. The current review focuses on the potential functions and mechanisms of osmolytes and how they relate to plants' ability to withstand abiotic stress. The information in this review will aid readers in learning more about osmolytes and how they respond to changing environmental conditions, as well as in developing an understanding of how this knowledge may be used to help plants adapt to stress.

Keywords: Osmoprotectants; Abiotic stress; Drought; Salinity; Amino acid; Carbohydrate; Polyamine; Polyol

Introduction

Plant diversity, production, and distribution are all influenced by environmental stressors. Unfavorable environmental circumstances hinder plants' ability to grow, develop, and reproduce. Worldwide, key environmental factors that limit plant productivity include salinity, water scarcity, water logging, toxic and inadequate nutrient levels, and cold or hot conditions. Low quality irrigation water, poor cultural practices, frequent drought conditions, unpredictable weather, and overall climate change are the main causes of environmental stresses. These environmental stress factors lead to low agricultural productivity of lands and food insecurity, particularly in developing countries. The ability of plants to employ their numerous defensive mechanisms effectively determines how long they will survive these pressures. According to Khan et al. (2012) and Sharma et al. (2016), abiotic stressors inhibit plant growth through influencing a variety of biochemical and physiological processes, including photosynthesis, antioxidant systems, and hormone signaling. Plants respond intricately to these environmental pressures in order to protect themselves from harm and improve their ability to survive challenging circumstances. Abiotic pressures eventually mount a plant's growth and development by altering several cellular and molecular processes (Bohnert et al., 1995; Shrama et al., 2019) [1-4].

Both heat and drought stress negatively impact plant development and physiology, according to a number of studies (Cui et al., 2022; Ayaz et al., 2021). Numerous physiological, biochemical, and molecular reactions to high temperature stress include stomatal closure because of low vapor pressure, which reduces the amount of carbon dioxide (CO_2) available (Mathur et al., 2014; Parrotta et al., 2021). Additionally, this can harm the photosynthetic machinery and lessen photosystem activity, which lowers the photosynthetic rate (Fv/Fm) and triggers a variety of physiological reactions, including an increase in proline concentration and a decrease in chlorophyll content (Thompson et al., 2022; Mafakheri et al., 2010) [5-7].

Osmolyte

In order to react to a stress, the plant uses stress sensors, signaling pathways, and metabolism. Osmolytes are low-molecular-weight molecules that are synthesized and accumulated as one such physiological reaction when a plant is exposed to stress. Osmolytes typically have no net charge at physiological pH, are readily soluble in

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water, do not interfere with typical metabolic processes, and are not hazardous even at high concentrations [8, 9]. These are also referred to as "compatible solutes" as a result (Slama et al., 2015). In general, osmolytes are identified by stress physiologists based on three types of data: (i) a rise in organic molecule accumulation under decreased water potential in cells; (ii) the physicochemical properties of the putative osmolyte when studied in vitro; and (iii) comparative physiology as a pointer to gain insight into whether osmolytes provide protection in desiccation-tolerant species or in dehydration-tolerant [10-12].

Major groups of osmolytes

Osmolytes, a class of phyto-protectants, can alter the solubility of water, regulate osmotic potential, maintained folded proteins, and safeguard the membrane structures in harsh climatic conditions (Yancey, 2005). Due to their ability to protect cellular components against osmotic, oxidative, and dehydration damage, these substances are known as osmoprotectants (Table 1). Osmolytes can be divided into the following groups:

Osmolyte variety in plants

Despite the fact that the majority of osmolytes found throughout the plant kingdom have species and environmental specific osmolytes (Slama et al., 2015). The concentration or accumulation of osmolytes varies similarly depending on heredity and environmental factors. For instance, the amino acid proline appears in a variety of taxonomically different plants, whereas the quaternary ammonium complex-alanine betaine accumulates among a few species of Plumbaginaceae (Gupta and Huang, 2014). In general, plant species that have experienced ongoing environmental stress in the past have evolved to store osmolytes [13,14].

Numerous studies have shown that under abiotic stress, plants gathered sugars like trehalose, mannitol, and galactinol. Several genes are involved in the biosynthesis of these organic solutes, which helps transgenic plants develop a tolerance to abiotic stress (Taji et al., 2002) [15]. Proline accumulation is likewise one of the processes or reactions that many plants use to adapt to diverse conditions (Anjum et al., 2015, 2016; 2017). Thus, it is crucial to comprehend the mechanisms governing various activities as well as the mechanisms underpinning plants' ability to withstand abiotic stress. Plants use phytohormones extensively in a variety of biochemical and physiological processes. For plants to be tolerant of unfavorable conditions, their involvement in reducing abiotic stress is essential (Khan et al., 2015; Tanveer et al., 2019; Shahzad et al., 2018; Khan et al., 2013; Sharma et al., 2019). It is essential to correlate the two because both osmolytes and plant hormones have been shown to play significant roles in stressful situations. This will help to clarify how phytohormones regulate osmolytes in response to abiotic stress [16,17].

Function of osmolyte in plant cell

The water intake necessary to sustain plant cell rigidity is caused by the osmolyte gradient, not the plasma membrane, which serves as an osmotic barrier. Plant cells' cytosolic aqueous gel-based osmolyte system controls fluid balance and volume of cells. Turgor dynamics are influenced by the presence of carbohydrates like D-glucose and amino acids like L-glutamine in the cytosol [18]. According to Argiolas et al. (2016), such osmolyte complexes increase the turgor pressure needed for plant movement. Sugars support the development of plant tissues and control signaling networks that manage the transcription of genes essential for respiration, photosynthesis, and the making of starch and sugars (Hare et al., 1998). Unbound amino acids which are building blocks of proteins, contain nitrogen (such as nucleic acids). Proline also decreases cytoplasmic acidosis and maintains the NADP+ to NADPH ratios necessary for metabolism (Hare et al., 1998) [19, 20].

Mechanism of action of osmolytes in plant cells

Abiotic stressors in plants result from environmental factors that disturb them enough to cause a reaction in them. Drought, salt, heavy metal toxicity, chilling, freezing, and heat stress are examples of abiotic stressors that are commonplace throughout the world and pose a threat to plant productivity and distribution [21].

Important osmo-protectants in plant cells

Low molecular weight hydrophilic organic molecules known as osmoprotectants play a number of roles in relation to plant defense mechanisms in a variety of environmental contexts (Nahar et al., 2016). These substances are not harmful at increasing cellular quantities, in contrast to inorganic substances (Niazian et al., 2021). Under stressful circumstances, plants buildup proline, ectoine, trehalose, polyols, fructan, and compounds with quaternary compounds (QACs), such as glycinebetaine, alanine-betaine, proline-betaine, choline-O-sulfate, hydroxy-prolinebetaine, and pipecolatebetaine (Singh et al., 2015). The quantities of molecules like mannitol, GB, D-ononitol, or sorbitol generated by transgenic plants overexpressing osmoprotectant biosynthetic enzymes are too little to give protective benefits only by osmotic mass action (Huang et al., 2000) [22-25].

The major purpose of osmoprotectant accumulation in plants under salt stress is to protect cellular components by reducing ionic toxicity and maintaining cell turgor pressure through osmoregulation. These osmoprotective compounds also strengthen plants' natural defense against free radicals by scavenging potentially harmful ROS while protecting vital antioxidative enzymes (Hasanuzzaman et al., 2014, 2019). Osmolytes also play a role in the activation of genes related to defense in response to a variety of stressors, which further emphasizes their critical role in plants (Wani et al., 2018b) [26].

Table 1: Major groups of osmolytes and its examples.

Groups of osmolytes	Plants in which found	Examples of Osmolytes
Amino Acids	*Aizoaceae, Asteraceae, Amaranthaceae,Anacardiaceae, Brassicaceae, Casuarinaceae, Cucurbitaceae, Cupressaceae, Cymodoceaceae,*	(Glycine, Proline, Alanine, Arginine) Amides: (glutamine and asparagine) Non-protein amino acids (pipecolic acid, ornithine, citrulline, and aminobutyric acid)
Quaternary ammonium compounds	*Asteraceae, Acanthaceae, Amaranthaceae, Brassicaceae,*	Proline betaine, hydroxyproline betaine, glycine betaine, alanine betaine, choline-O-sulphate, and pipecolate betaine
Sugars	*Asteraceae, Ama ranthaceae, Cyperaceae, Juncaceae*	Fructan, sucrose and trehalose
Sugar alcohol (Polyols)	*Apiaceae, Asteraceae, Combretaceae, Cymodoceaeceae, Fabaceae and Plantaginaceae.*	D-Ononitol, inositol, mannitol, pinitol and sorbitol.

Amino acids

Examples of amino acids with osmoprotective origins include proline, arginine, alanine, and aminobutyric acid (GABA; Suprasanna et al., 2014). These osmoprotectants accumulate and reduce the osmotic potential of cells during salt stress, increasing water absorption [27]. They also maintain the structural integrity of proteins and membranes (Ashraf and Foolad, 2007), act as nitrogen-storing agencies and ROS scavengers (Hayat et al., 2012), and store nitrogen. Stressed situations are indicated by the buildup of primarily proline in substantially higher proportions than other osmoprotectants. Alanine serves as a stress response molecule in plants' defense against biotic and abiotic stresses as it is a non-proteinogenic amino acid. Furthermore, it is changed into the osmo-protective compound in various plant species (Parthasarathy et al., 2019) [30].

Proline

Glutamate and the ornithine route are the two mechanisms that can produce proline. The intermediate 1-pyrroline-5-carboxylate (P5C), which is catalyzed by 1-pyrroline-5-carboxylate synthetase (P5CS) and 1-pyrroline-5-carboxylate reductase (P5CR) in the glutamate route, is used to create proline from glutamatic acid (Dar et al., 2016). The alternative process, described by Verbruggen and Hermans (2008), involves the synthesis of proline to ornithine, which is then transaminated to pyrroline-5-carboxylate (P5C) [31]. Proline accumulation is said to help with stress tolerance in a variety of ways. It serves as a biochemical chaperone, maintaining the integrity of proteins and fostering enzyme activity (Ghosh et al., 2022). The expression of the enzyme pyrroline-5-carboxylate reductase has recently enhanced in engineered plants, resulting in an accumulation of proline [32].

Additionally, proline's antioxidant properties have been found to be useful as reactive oxygen species scavengers (El-Badri et al., 2021). Through the constitutive expression of OsOAT genes, it has been demonstrated how crucial the ornithine path is involve in growth of rice seedlings. According to You et al. (2012), these genes are in charge of better antioxidant status, increased-OAT activity, and tolerance to osmotic stress and drought. However, due to higher expression of P5CS activity during salt stress, the Glu pathway is used more frequently than the Orn pathway. This shows that proline accumulation during osmotic adjustment is significantly influenced by the Glu route (Zhen and Ma, 2009) [33].

In Vigna aconitifolia L. under salt stress, P5CS mRNA levels dramatically increased whereas OAT mRNA levels significantly decreased, according to Delauney et al. (1993). Later, it was verified by evaluation studies looking at proline biosynthesis under salt stress by Lei et al. (2016) and Mansour and Ali (2017). It is interesting that exogenous proline administration led to various outcomes. For example, Zea mays L [34]. underwent salt stress and experienced decreased P5CS activity and increased PDH activity due to foliar proline exposure (de Freitas et al., 2018). Under salinized circumstances, Sorghum bicolor showed comparable results (de Freitas et al., 2019). Exogenous proline-primed seed has been associated with reduced P5CS response, whereas Triticum aestivum L. PDH expression has dramatically enhanced (Rady et al., 2019). According to Deuschle et al. (2001), these elevated PDH levels shield plants from the toxicity of proline. Proline builds up and antioxidative responses to salt stress are improved in Lepidium draba when the P5CS gene is overexpressed (Pakzad et al., 2021) [35,36].

Glycine betaine (GB)

Glycine betaine (GB), an ammonium molecule that is an N-methylated by-product of glycine and is zwitterionic, neutral at physiological pH, as described by Ashraf and Foolad (2007). Chloroplasts in young tissues produce GB in large quantities to protect membrane enzymes and proteins from harmful environmental factors. Because GB is not actively broken down or metabolized in plant tissues, GB concentration is regulated by plant synthesis, transport, and dilution (Annunziata et al., 2019) [37]. Under abiotic stress situations, GB is biosynthesized as spatiotemporal (Annunziata et al., 2019). Biological stress usually starts out at minimal amounts and builds up over time in developing tissues and organs. Furthermore, unlike proline, the GB is swiftly re-translocated to younger leaves even when exogenously given to older portions. Therefore, it can be concluded that GB cannot be metabolized and is essential for protecting developing tissues (Figure 1) [38].

Sugars

Carbohydrates such sugars (including sucrose, fructose, and trehalose) and starch build up during salt stress (Parida et al., 2004). These sugars are important because they act as an osmoprotectant and a ROS scavenger to reduce salt stress. Additionally, it has been noted that as salt stress levels rise, lowering sugar levels (such as fructans and sucrose) rise dramatically as well (Kerepesi and Galiba, 2000; Gangola and Ramadoss, 2018) [39,40].

Sugar alcohol

Sugar alcohols such as pinitol, mannitol, myo-inositol, and sorbitol play a vital role in lowering stress-related diseases by altering the osmotic equilibrium. These also have a strong polyol reputation. Myo-inositol and pinitol are cyclic, but mannitol and sorbitol have a linear structure. Their buildup in plants is thought to serve a variety of purposes, including osmotic adjustment, ROS regulation, and molecular chaperons, according to Upadhyay et al. (2015) and Bhattacharya and Kundu (2020) [41]. A sugar alcohol called mannitol is created when the enzyme mannose-6-phosphate reductase reacts with a combination of glucose and fructose to produce both mannitol and gluconic acid. According to Kaya et al. (2013), mannitol helps with osmotic balance and removes oxygen radicals generated by stress. An osmoprotectant called sorbitol is created during photosynthesis (Wu

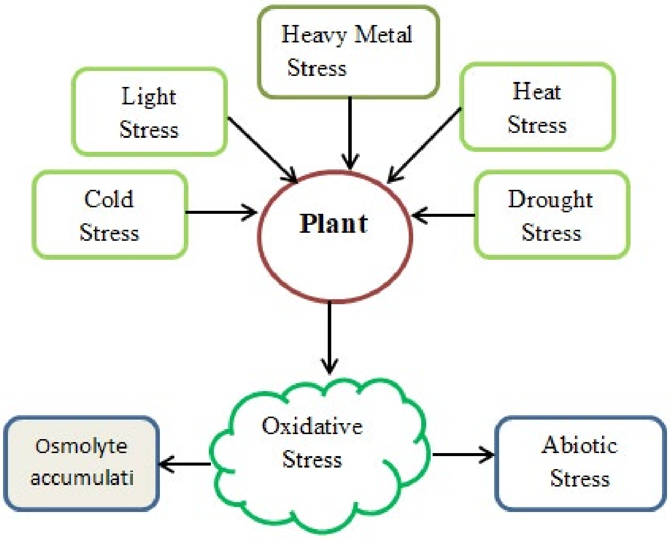

Figure 1: Schematic representation of Plant response to various abiotic stress factors.

et al., 2020). Zhou et al. (2003) converted sorbitol-6-phosphate into sorbitol by dephosphorylating sorbitol-6-phosphatase. As an osmolyte, d-ononitol, a sugar alcohol, prevents water loss in plants that are under drought stress [42]. Tobacco was able to manufacture more D-ononitol and show greater resistance to salt and drought by adding the myo-inositol O-methyltransferase gene (Vinocur and Altman, 2005). Pinitol is a byproduct of the methylation of myo-inositol and is found in a number of halophytic organisms. As a consequence of ononitol epimerization, pinitol is also created (Sengupta et al., 2008; Slama et al., 2015; Dumschott et al., 2019) [43].

Inositol

Numerous plants produce the sugar-like carbohydrate known as inositol, or more specifically, myo-inositol (Valluru & Van den Ende, 2011; Nisa et al., 2016). Pinitol, galactinol, and ononitol are some of its derivatives that function as osmoprotectants in a number of ways (Handa et al., 2018). Additionally, it controls the manufacture of phytic acid, auxin, and plant defense mechanisms (Hazra et al., 2019) [44]. In two different mechanisms, inositol and other related compounds are proposed to demonstrate salt tolerance: (1) by protecting the interior of cells from ROS, and (2) by preserving cell turgor stress. The generation of the polar compound (inositol) is a two-step metabolic process way that starts the enzymatic transformation of the sugar d-6-P into myo-inositol-1-P stimulated by myo-inositol-1-P synthase (Majumder et al., 1997), accompanied by the dephosphorylation of myo-inositol-1-P resulting to generate myoinositol which further generates distinctive inositol-containing materials including the phospholipids (Dastidar et al., 2006) [45].

Polyamines

Low molecular weight nitrogen-containing substances known as polyamines (PAs) are found in several cellular compartments. The three plant growth substances spermidine (Spd), putrescine (Put), and spermine (Spm) are the most prevalent PAs detected in plants (Bano et al., 2020). Canavalamine, homospermidine, cadaverine, and 1, 3-diamino propane is among the additional PAs that can be made from amino acids. The most common forms of PAs are free or coupled with phenolic chemicals, macromolecules, or both. putrescine (Put), spermidine (Spd), and spermine (Spm) are the most abundant PA that can be formed from arginine with the help of N-carbamoyl putrescine and agmatine (Urano et al., 2003) [46]. The synthase enzyme also transforms this putrescine into spermine and spermidine. Out of these polyamines, putrescine is the one that accumulates most in saline environments. Due to their polyanionic nature, they engage with the outer layer of the membrane and assist in maintaining the membrane structure (Gill and Tuteja, 2010a) [47]. Polyamines' main roles, according to Kuznetsov et al. (2007), Mustafavi et al. (2018), and Chen et al. (2019), are osmotic regulation, hydroxyl radical scavenging through altering the activity of enzymes and ammonia detoxification. According to Li and He (2012), Spd level may serve as a marker of one's ability to tolerate salt. Exogenous Spd treatment enhanced growth of plants by increasing photosynthesis and reactive oxygen metabolism in the presence of salinity stress (Meng et al., 2015; Baniasadi et al., 2018) [48-50]. The expression of polyamine biosynthetic enzymes like spermidine synthase (SPDS), arginine decarboxylase (ADC), ornithine decarboxylase (ODC), and S-adenosyl methionine decarboxylase (SAMDC) is utilized in a variety of transgenic techniques to improve stress tolerance (Gill and Tuteja, 2010a). Following validation of the subpar performance of transgenic plants altered with PA synthesis genes (Urano et al., 2004; Marco et al., 2015), regulation of PAs becomes critical in salt-stressed plants. Brassica napus L. is capable of reducing the negative effects of salt thanks to up-regulated expression of Calvin-cycle-related genes mediated by PAs (ElSayed et al., 2022) (Figure 2) [51-53].

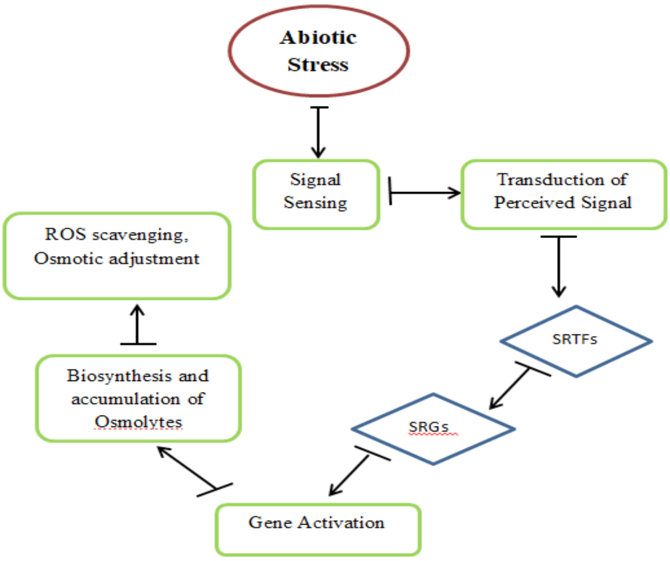

Figure 2: Schematic representation of abiotic stress and osmolyte (Pathway is initiated as results in induction of stress responsive transcriptional factors (SRTFs) that up regulate the stress responsive genes (SRGs) related to biosynthesis and accumulation of osmolytes.

Ionic tolerance

A well-known strategy allowing agricultural plants to tolerate salinity is the exclusion of ions, especially Na+, from the shoot [54]. Due to the ease of conducting experiments, this mechanism has drawn the greatest attention. Many crops, including wheat (Forster, 2001; Munns and James, 2003), rice (Zhu et al., 2001; Lee et al., 2003), barley (Wei et al., 2003; Garthwaite et al., 2005), and Medicago (Sibole et al., 2003), have shown a significant connection between exclusion and salt tolerance. With this technique, Na+ and Cl-penetrate the plant's roots and quickly travel to the shoot by the process of transpiration. In order to avoid these ions from accumulating in the shoot system, the roots filter out the majority of the Na+ and Cl dissolving in the soil solution [55-60]. As a result, the plant may survive in saline soil indefinitely since the concentration of salt in the shoot as a whole never exceeds that in the soil. Because the concentration of Na+ and Cl ions is far higher in the shoot than in the roots, this boosts the plant's tolerance to salt. The sodium and other ion concentrations in the various layers of wheat root were assessed by Lauchli et al. (2008Additionally, the first line of defense against sodium uptake is the SOS1 antiporter, which is located to the root epidermis (specifically at the root tip, where roots are undifferentiated) (Assaha et al., 2017) (Figure 3) [61-65].

Bioengineering: Osmolyte induced stress tolerances

The relevance of osmolytes during abiotic stress responses has been well investigated thanks to bioengineering of the genes responsible for osmolytes' biosynthesis and metabolism (Groppa and Benavides, 2008). Abiotic stress tolerance has been used to confirm the increased level of compatible nontoxic osmolytes, radical scavengers, and other transgenic products (Vinocur and Altman, 2005) [66-68]. Due to advancements in biochemical and cell biology techniques, it is now possible to clone potential osmolyte biosynthetic genes and transfer them into essential crop plants (Wang et al., 2003). According to

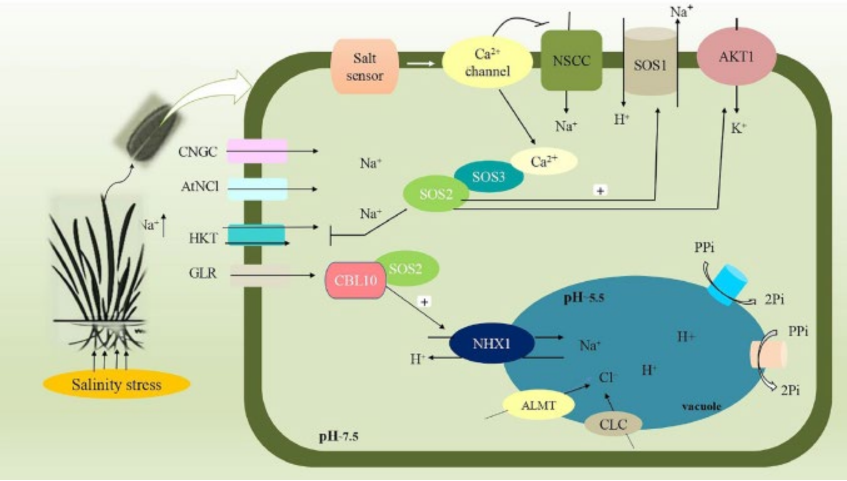

Figure 3: Schematic diagram of salt overlay sensitive (SOS) pathways. (Pooja Singh et al., 2022).

Cortina and Culianez-Macia (2005), the trehalose biosynthetic pathway alters carbohydrates, which may explain why tomato plants with the TPS1 gene displayed higher tolerance when utilized with yeast [69,70]. Engineered tobacco cell lines containing ect A, ect B, and ect C showed improved resistance to mannitol-induced osmotic stress, which is linked to the constitutive CaMV 35S promoter (Nakayama et al., 2000) [71,72]. By boosting transpiration and safeguarding RuBisCO proteins, they also showed increased nitrogen delivery to leaves (Moghaieb et al., 2006). Revealed that engineered plant lines of Petunia hybrida were created using 1-pyrroline-5-carboxylate synthetase genes (AtP5CS gene obtained from Arabidopsis thaliana L [73,74]. or OsP5CS gene derived from Oryza sativa L.) that showed improved tolerance to conditions of drought and accumulated additional proline. Greater tolerance to drought stress was also seen in transgenic wheat plants (VaP5CS from Vigna aconitifolia) (Vendruscolo et al., 2007) [75-79]. P5CR was overexpressed in Arabidopsis under abiotic stress conditions such as salt, polyethylene glycine, abscisic acid, and heat stress. Furthermore, proline P5CR expression in soybean (Glycine max L. Merr. cv. Ibis) with greater endurance to drought resulted in increased accumulation of proline (Simon et al., 2006; Mwenye et al., 2016) [80]. It is reported that the choline dehydrogenase (betA)-producing choline dehydrogenase (DH4866) genetically engineered line of maize showed higher GB storage and stress caused by drought resistance [81-84]. In plants exposed to stress conditions, improved osmotic adjustment, reduced ion leakage, lipid membrane peroxidation, and improved level of relative water content are potential indications of drought resistance (Lv S et al., 2007) [85-90]. A research study shows that under both ordinary and salt stress (150 mM NaCl), transgenic cotton produced by introducing the CMO gene (AhCMO) replicated from Atriplex hortensis collected more GB than nontransgenic plants. The betA gene has been introduced into wheat, and this wheat has shown resistance to salt stress (He et al., 2010). Furthermore, it has been demonstrated that chloroplast genetic engineering's overexpression of betaine under the direction of betaine aldehyde dehydrogenase (BADH) is a key tactic for providing salt tolerance to particular crops (Kumar et al., 2004; Fitzgerald et al., 2009). Additionally, tobacco plants that had the BADH gene for betaine aldehyde dehydrogenase added to them had the ability to produce GB in chloroplasts that induced salt stress [91-94].

Conclusions and Perspectives

The positive impacts of osmolytes have on plants as well as their ability to boost abiotic stress tolerance were highlighted in this review study. One possibility for achieving the second environmentally friendly goal, which is to end hunger, is to increase both the quantity and the quality of agricultural crops through the synthesis of osmolytes and their stress-reduction properties. However, other economically successful crops, such as wheat, maize, and barley, do not produce higher amounts of osmolytes. Comparatively to susceptible genotypes, only stress tolerant genotypes within a species accrue levels of osmolytes high enough to deal with stress. As a result, numerous studies have demonstrated that exogenous osmolyte treatment can compensate for osmolyte accumulation deficiencies and improve plant growth. Exogenously given osmolytes help plants fight against environmental stress more effectively than unfed plants do, even within the same accumulating species. Furthermore, exogenous administration of a particular osmolyte or mixtures of osmolytes reduces the negative effects of a particular stress state in cells. In order to help a particular crop deal with a particular stress, researchers have advised exogenous administration of a particular osmolyte. A number of studies have shown that the biosynthetic and regulatory genes from various sources have been effectively used to create transgenic plants that are more resistant to stress and have the capacity to accumulate osmolytes in a timely manner. The numerous potential genes for the osmolyte synthesis pathway can be advantageous for a variety of crop plants. Due to the quick worldwide changes in the climate, research must focus on utilizing the benefits of osmolyte-mediated crop enhancement to assist the worldwide supply of food. Improvements in gene implantation and manipulation may facilitate the development of super crops by enhancing their capacity to retain osmolytes for greater production and to ensure life under various stress conditions.

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