Innovations

Unravelling the Role of Gallic Acid in Imparting Abiotic Stress Tolerance in Legumes

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Abstract : *Abiotic stressors such as salinity, heavy metals, temperature, drought, etc, significantly hinder growth and yield of legume crop. All of these stressors affect metabolic processes, nutritional availability, and water absorption, which results in oxidative stress, ion toxicity, and osmotic imbalances especially in legumes. Collectively, these stressors induce morpho-anatomical, physiological, and biochemical alterations, leading to substantial economic losses in legume crop production. Although, plants employed diverse inherent defense mechanisms like metal sequestration, antioxidant enzymes activation, osmolytes synthesis, etc. to combat the negative impact of these stressors, however, still there is a need of efficient alternative approach for sustainable agriculture practices.Recently, GA is identified as a key regulator that promotes root formation, secondary metabolite synthesis, and facilitates the plant defense system under various stressed conditions. Keeping this in view, the present review explores the multifaceted role of Gallic Acid (GA) in improving abiotic stress resilience in legumes. The findings suggest that GA may serve as a sustainable strategy to mitigate the adverse effects of abiotic stress on legume productivity and resilience.*

Keywords: *Abiotic stress, antioxidant, gallic acid,legumes, osmolytes, reactive oxygen species*

Introduction:

Abiotic stressors, including salinity, high temperature, drought, flood, heavy metal, etc., have a substantial negative impact on the growth and yielding potential of agricultural crops(Kopecká et al., 2023).Around the world, 20% of agricultural cultivation has been affected by salt stress (Liu et al., 2019). Salinity reduces the plant's growth by decreasing the water absorption rate and increasing the concentration of ions ($Na^{+,}$ Cl^{+}, K^{+}) inside the cell which, ultimately alter the water status of the plant tissues (Afefe et al., 2022). Overall, under salinity stress plants undergoes to various oxidative, osmotic, and ionic stressed conditions. Similarly, nowadays HM stress becoming a significant issue that has a negative impact on the soil fertility and crop productivity (Zia-ur-Rehman et al., 2023). Concentration of heavy metals like aluminium (Al),cadmium (Cd), chromium (Cr), arsenic (As), lead (Pb), mercury (Hg), etc. are building up in the soil due to various manmade and natural processes which ultimately affect the growth and productivity of plant (Khatun et al.,2022). Apart from that temperature (cold and heat), drought, flooding, etc. are other abiotic stressors that restricts growth and developmentof plants. Overall, all these abiotic stressors induce a range of morpho-anatomical, physiological, and biochemical alterations in plants, resulting in a significant decrease in economic yield (Ul Hassan et al., 2021).

Plants undergo various metabolic changes in response to environmental stressors, which frequently have an adverse effect on growth and yield. Salinity inhibits the germination of crops plants by either producing an osmotic potential that prevents water uptake or by the hazardous effects of Na^{+} (Sodium) and Cl^{-} (Calcium) ions (Khajeh-Hosseini et al., 2003).Reduced relative water content, osmotic damage, ionic imbalance, and reactive oxygen species production are all strongly associated with cellular damage caused by salinity (Shahid et al., 2020).Heavy metals can cause cellular redox imbalance, protein oxidation, accumulation of reactive oxygen species (ROS), disruption of nutrient uptake, inhibition of antioxidative enzymes, etc(Sperdouli,2022).For example, Cd toxicity reduced the growth and productivity of lentil plants by inducing the production of ROS (Bansal et al., 2021).Similarly, Pb-toxicity led to negative effects on seed germination and early crop growth in Vigna radiata (Ashraf et al.,2007), Medicago sativa(Sedzik et al., 2015), Lens culinaris(Cokkizgin,2010). Additionally, under zinc stress growth of pigeon pea decreased at various stages of development (Khudsaret al., 2008). Coldstress prevents lateral root growth and limit the absorption of water and nutrients from the soil (Sanders andMarkhart, 2023).Despite this, UV radiations can also harm the plants by inducing diverse changes at physiological and biochemical levels, and thereby, reduce the growth and development of plants (Qian et al., 2021). Plant development is also hampered by drought stress, which is also a major concern of current era (Bashir et al., 2021). Overall, changing environmental conditions have a damaging impact on growth and productivity of all the agricultural crops.

Plants have developed a number of defence mechanisms in order to cope with unfavourable environmental circumstances which, include metal sequestration within vacuoles, binding to phytochelatins and metallothionein's as well as the activation of antioxidant defense system, etc (Rasheed et al., 2021).Under unfavourable circumstance, enzymatic antioxidants, including ascorbate peroxidase (APX), superoxide dismutase (SOD), catalase (CAT) etc. and non-enzymatic antioxidants such as flavonoids, phenols, glutathione, ascorbate, etc. get activated to catalyse the conversion of damaging ROS into less hazardous compounds (Abdulfatah,2022).Moreover, plants accelerate the synthesis and storage variousosmo protectants, such as amino acids, glycine betaine, soluble sugars, polyols, and polyamines to combat the adverse conditions (Rasheed et al., 2024). Osmolytes have the great potential in scavenging reactive oxygen species and thereby, lowering the oxidative damage (Ejaz et al.,2020).Interestingly, heat shock proteins (HSPs) areessential for maintaining cellular homeostasis and plant survival during heat stressed conditions (Khan and Shahwar, 2020). Although plant have multiple defence mechanisms, however, under severe drastic conditions all these strategies are not able to alleviate the detrimental effect of abiotic stressors on plants completely (Sachdev et al., 2021).

Legumes are widely known for their health and nutritional advantages as well as their contribution to agricultural systems' sustainability (Kebede, 2021). Leguminosae, often known as Fabaceae, are second only to cereals in terms of food production; they provide 33% of the world's protein needs and 27% of its main crop production (Smýkal, 2015).Most importantlegume crops such as pigeon pea, chickpea, peanuts, soybean gaining most attention because they are needed in the higher amount due to their oil ending values and the major source of protein is pulses. Moreover, legumes have the ability to fix atmospheric nitrogen by the help of bacterium, Rhizobium, and thereby, offers a resource- and input-saving alternative by lowering the requirement for chemical fertilizers (Zhang et al.,2021). However, grain quality and composition of food legumes are adversely affected by various abiotic stressors. Under unfavourable conditions, the ability of legume plants to absorb nitrate from the soil solution get ceased which, ultimately reduced the protein content in seeds (Nadeem et al., 2019). Furthermore, abiotic stresses alter the nutrient uptake efficiency of plants and thereby, decline the phosphorus, nitrogen, potassium, levels in grains(Farooq et al., 2018). In a nutshell, abiotic stressors have adverse impact on the content quality and productivity potentially of the grain legumes.

In order to mitigate the impact of diverse abiotic stressors, suitable alternative approaches are required to nullify the impact of these environmental constraints, in as sustainable manner.Nowadays, application of various phenolic compounds to the agricultural crop is emerging as one of the strategies to impart tolerance to the plants. Among the various phenolics, Gallic acid (GA; also known as 3,4,5 -trihydroxy benzoic acid) with the formula $C_6H_{12}O_6$, is molecule which regulate multiple functions in plant (Wani, 2023).GA provides tolerance to the plants by modulating various mechanism for example, root formation, synthesis of secondary metabolites,chelation of HMs, synthesis of osmolytes, etc (Kumar et al.,2023). Moreover, an increase in the synthesis of GA within the plants help the plants to withstand UV radiation(Luna-Domínguezet al., 2023). GAis able to activate the plant defence system under cold stress also. For instance, soybean plants subjected to cold stress displayed reduced H_2O_2level and increased SOD, CAT, and POX activity when treated with GA (Yildiztugay et al., 2017). GA has also been reported in increase phenols, flavonoids, and callose content in rice plants which was correlated to reduced ROS content (Singh et al., 2017).Similarly, GA supplementation reduced the intensity of Cu toxicity on maize plants by

reducing the consequences of oxidative stress (Yetişsinandkurt, 2020). Overall, due to multifarious role of GA it could be used as a potential strategy to attenuate the negative impact of abiotic stressors on plants, including legumes.
Keeping all this in mind, the current review provides a comprehensive assemblage on role of GA in imparting abiotic stress tolerance to the legumes. Furthermore, the study will unravel the mechanism adopted by GA in enhancing the resilience of legumes towards various abiotic stressors, through sustainable manner.

Effect of abiotic stress on legumes

Abiotic stressors have different effects on legumes' grain composition and quality.Legume crops are strongly affected by abiotic stressors such drought, salinity, heat, cold, and heavy metals, which change their physiology, molecular processes and grain quality(Table 1). Legumes are vital for human nutrition and food security, yet these pressures lower their yield, protein content, and other vital components which alter these grain constituents as well as the nutritional value of legumes(Farooq et al., 2018;Sarkar et al., 2021).The impact of abiotic stressors on various legumes have been discussed, in detail, below:

Temperature stress

Depending on the season in which they grow, food legumes can be divided into two categories: warm- or tropical-season and cool-season (Hossain et al., 2023). soybeans, cowpeas,mung beans, black grams, pigeon peas, peanuts, and common beans, are primarily farmed in hot, humid climates therefore, known as tropical legumes. Contrastingly, the legumes that grow under temperate conditions are consideredas cool-season food legumes and example include broad beans, dry beans, peas, chickpeas, pasture peas, and lentils (Gotor and Marraccini, 2021). The performance of food legumes is reduced at different phases of growth due to their varying degrees of susceptibility to high and low temperatures (Bhandari et al.,2017). In food legumes, both high and low temperatures can cause stress if they rise or fall above the necessary threshold value responsible for healthy growth and development of plants.All the stages of seed setting, including the growth of male and female gametophytes, fertilization, and seed development, are susceptible to heat stress,therefore, heat stress negatively impacts the seed output and quality of food legumes (Liu et al., 2019).Heat stress has an effect on the grain development of food legumes because it breaks down the grain's tapetum layer, which lowers the nutrient supply to the microspores (Sita et al., 2017). This impairment causes an early anther dehiscence, hinders the synthesis and distribution of carbohydrates to the grain, and results in fractured embryos and poor pods, all of which lower grain yield (Sita et al.,2018).Increasing temperatures can also reduce the amount of total non-structural carbohydrates, and several food legumes. For example, soyabean plant showed a drop in the ratio of soluble sugars to starch under high temperature stress (Sehgal et al., 2018).Devi et al. (2022) reported that under heat stressed conditions pollen viability germination, seed yield, photosynthetic efficiency and water status declined in different genotypes of chickpea.Similarly, under temperature stress a significant decline in pod set, seed set and yield were reported by Karavidas et al. (2022) in Phaseolous vulgaris L. Similarly, mungbeanplants were more negatively affected by heat stress during the reproductive stage than the vegetative stage (Priya et al., 2020).According to Devasirvatham et al.(2012), during blooming and the development of floral organs heat stress caused a considerable loss in yield of chickpea.

Low temperatures stress, also known as cold stress, is characterized by a temperature that falls below the ideal range needed for a crop's healthy growth and development, resulting in harm or irreparable damage to the crop. Cold stress had negative effect on vegetative phases as well as their reproductive growth and grain composition of legumes (Farooq et al., 2018).Grain filling in plant depends on the source-sink connection, deteriorates under low temperature conditions, therefore leads to reduction ingrain filling (Xu et al., 2022). Cold stress also inhibits the storage of proteins, minerals, and amino acids in dietary legume grains. For instance, cold stress reduced the accumulation of stored amino acids, protein, starch, fat, and crude fibre and thereby, led to reduced growth of chickpea (Yagoob, 2014).According to Maqbool et al. (2010), soybean (Glycine max) displayed signs of damage when exposed to temperatures below 10 to 15°C. Wery et al.(1993) reported that the plant of pigeonpea died in cold weather due to cell dehydration and membrane breakdown.Moreover,Choudhary et al. in(2011) reported that low temperatures caused intercellular water to turn into ice, which caused cells contraction and death of pigeonpea.A study conducted by Jan et al. (2023) revealed that yield of legume crops, including chickpeas, soybeans, and Mungbeandecreased between 60 to 70% due to cold stress. According to Hajihashemi et al. (2018), peanut plants exposed chilling environment displayed significantdecline in seedling growth,leaf area and the dry matter productionin aboveground and belowground parts.

Drought stress

One of the main factors limiting the production of food legumes is drought, particularly in the dry and semi-arid tropics. Drought during the stages of grain growth is particularly problematic because it significantly reduces yield (Ghanbari et al., 2013). In legumes, drought alters the composition and quality ofgrains by lowering the uptake of N, P, Fe, and Zn.Ashrafi et al. (2015) reported that underdrought stress the fatty acid composition of soybean grains get altered, which in turn changed the soybean's overall oil composition, stability, and level, particularly during grain filling. Under drought, the mature grain of the common bean and soybean displayed lower levels of starch and soluble sugars, respectively (Farooq et al., 2017). Grain and food legume mineral content is significantly impacted by drought. Farooq et al. (2018) reported that the levels of sodium (Na), potassium (K), and calcium (Ca) decreased in chickpea plants under drought stress. Grainyield of legumes lowered by drought stress at several phenological stages of crop growth. According to Mafakheri et al.(2010)the drought-tolerant variety of chickpea i.e. "Bivaniej" displayed higher yield when compared with drought sensitive variety i.e. "Pirouz".Labanauskas et al. (1981) reported thatin cowpea seeds' protein–amino acid fraction decreased as a result of drought stress throughout the blooming and pod filling stages.Drought stress decreased the soybean development and yield by reducing the root growth and biomass during early vegetative stage (Tarumingkeng, and Coto2003). Because of the abortion of the flower, drought stress during reproductive growth shortened the floweringtime and decreased the number of flowers, seeds, and pods in soybean plants.Drought stress led to reduced seed germination, stunted development, damaged photosynthetic machinery, and declined net photosynthesis as well as nutrient uptake in black gram (Pandiyan,2023). Similarly, drought stress caused reduced germination,water status, shoot and root growth as well as membrane stability in lentils (Singh et al., 2017; Biju et al., 2018; Akter, 2021; Ben Ghoulam, 2022). According to Baroowaand Gogoi2012), drought stress had a major impact on the plant growth of black and green grams, thereby, resulting in decreased yield and productivity.

Salinity stress

One of the main issues in arid and semi-arid regions, which make up almost 40% of the earth's total area, is salt stress. It is a major barrier to the development of food legumes. Salinity stress disrupts the quality of dietary legumes and grain composition by altering hormone interactions, leading to ionic toxicity, osmotic consequences, and nutritional imbalance (Torabian et al., 2018;Nadeem et al., 2019).Food legumes' competitive nutrient absorption, accumulation, and transport are disrupted by salt stress. Salt stress damages plants by causing an ionic imbalance, primarily of K+, Na+ and Ca2+ ions (Garg et al., 2016).Since sodium (Na+) and chloride (Cl−) ions disrupt uptake of vital nutrients like N,P,K,Ca, Zn,B, Mg, Cuand Fe, the presence of these ions in the rhizosphere region caused nutritional imbalance in bean plants (Khan, 2017).Due to disruptions in nitrogenmetabolism of dietary legumes, salt stress has a significant impact on oil and grain protein levels (Amiraand Qados, 2010). Due to salt stress, stigma receptivity, pollen viability, and photo assimilate supply decrease during grain filling, thus lowering food legume grain production (Sehrawat et al.,2019).On the other hand, during salt stress, the legume grain's total amino acid content decreased, which in turn the N uptake (Ahmad et al., 2011). Increased concentration of salinity in the soil led to reduction in the concentrations of K and P in the mung bean grains, thus led to nutritional imbalance in the plants (Khanet al., 2016).Delgadoet al. in(1994) reported the adverse effect of salt stress on nitrogen fixation ability and respiratory capacity of Bacteroidesin soybean, pea, faba-bean and bean plant. According to the findings, G. max was the species that could withstand the higher concentration of salt, while P. savitum was the legume more prone to the salinity(Ahmad et al., 2024). Ferri et al.(2000) reported thatunder salt stress P. vulgaris showed inhibition in growth, nodule dry weight, and acetylene reduction activity (ARA).Prakash in(2017)observed a significant decline in germination percentage, seedling length, dry matter production, seed vigor, and salt tolerance index in green gram at higher salinity levels (12 ds/m). A recent study conducted by Amel et al. (2025) observed increased accumulation of proline and non-enzymatic antioxidants and reduced biomass, water content and root length of faba bean under salinity stress.When the effects of salinity on photosynthesis and chlorophyll fluorescence were examined in Medicago truncatula, the total chlorophyll content was considerably lower in TN6.18 (down 43%) and TN.8.20 (down 6%)genotypes than the control plants (Najar et al., 2019).

Heavy metal stress (HM)

Heavy metal deposition in soil, is a major constraint for agricultural crops (Hossain et al.,2010; Pokhrel et al., 2009). These HM impair the yield and quality of food legumes when they are present in the rhizosphere zone at levels higher than the ideal. They can also pose health risks to humans by accumulating in the grains of food legumes (Shi et al., 2010).Heavy metal toxicity results in poor plant development, chlorosis, a loss in yield that is augmented by a decrease in nutrient intake, problems with plant metabolism, and a diminished capacity to fix nitrogen molecules (Asati et al., 2016).Heavy metalscan alter the content of major and minor fatty acids in dietary legumes. For example, under metal stress, oleic and linoleic acid content fell dramatically in soybean plants, while stearic, linolenic, and palmitic acid, content displayed a significant improvement (Weiand Cen,2020).With the exception of chickpeas and mung beans, the grain protein content of the majority of dietary legumes dropped as the concentration of Cd, Cr, Ni, Zn, Pb, and Cu increased in the rooting medium (Lebraziand Fikri, 2018). Application of Zn to chickpea significantly reduced the growth and productivity of plants by altering nutrient acquisition (Valentine et al., 2018).According to Shaffique et al. (2023) soybeans plants displayed vulnerability to heavy metal toxicity, which impacted the growth, photosynthesis, and seed quality. Oxidative stress caused by heavy metal exposure in soybeans interfered with various cellular functions and reduced the growth and productivity of plants (Liu et al., 2023). Moreover, Sarkar et al.(2022) investigated the bioaccumulation potential in legumes and found traces of heavy metals in the edible components, which poses a concern to food safety. Thallapally and Thirunahari(2024) correlated the increased Cd concentrations with the altered ultrastructure of root nodules, which lowered the effective N_2-fixing area and N_2-fixing cells in black gram.According to a current study, Vigna radiata seedlings showed more sensitivity to zinc than to copper, indicating differential tolerability of plants towards various heavy metals (Nupur, 2025). In mungbean, Kaya et al. (2020) discovered dramatical decrease in above-ground biomass relative to below-ground biomass when exposed to Cd.

UV stress

The main energy source for Earth's photosynthetic life is the sun. Because of the stratospheric ozone (O_3) layer's depletion, ultraviolet-B (UV-B, 315–280 nm) radiation is a naturally occurring component of solar light that reaches the Earth's surface. But many studies shows that UV-B radiation has a negative impact on plant morphology, biochemistry, and physiology (Choudhary et al.,2017).In legumes, UV-B rays can decrease plant height, leaf size, and total biomass, elongation of roots and nutrient uptake (Guruprasad et al., 2007; Qaderi et al., 2018). UV-B radiations have damaging impact on photosynthetic machinery of the plant which interferes with the photosynthetic process and leads to reduction in photosynthetic rates (Singhet al**.,** 2019). Moreover, this radiation can hamper the growth and productivity of legumes by interrupting the blooming phase, development of buds and pods and quality of the seeds(SinhaandHader,2021). For instance, Kataria et al. (2017), reported the detrimental impact of UV-B exposure on root growth and water as well as nutrient acquisition in soyabean plants. Similarly, when Abrus precatorium and Vigna mungowere exposed to UV-B radiations by Doss et al. (2022), plants displayed higher production of secondary metabolites as well as anti-nutritional factors. A significant reduction in plant height, root and shoot length, chlorophyll content was observed in UV-B treated pea plants (Jenishree et al., 2024). Similarly, Singh et al. (2015) observed higher production of ROS and reduced nitrogen fixation ability of pea plants under elevated UV-B radiation. Cowpea plants displayed a significant reduction in biomass accumulation nutrient acquisition (especially N) and nitrogen fixation potential when treated with UV-B radiation (Ayalew et al., 2022).

Overall, changes such as reduction in growthwater status, nutrient uptake, chlorophyll synthesis, production of oxidative stress marker, etc. are the major responses induced by various abiotic stressors. All these abiotic stressors have negative impact on growth and productivity potential of legumes, which is a major concern for developing and developed nations. Although plants have their own inherent machinery, for example, activation of antioxidant mechanisms, synthesis of osmolytes, upregulation of stress responsive genes, etc., however, all these mechanisms are not sufficient under drastic conditions (Hasanuzzaman et al., 2020). Therefore, there is a dire need of some exogenous strategies to impart tolerance to the plants.

Gallic acid: Introduction & Biosynthesis

Gallic acid (GA), a phenolic molecule found in a variety of fruits and vegetables, is increasingly recognized for its ability to reduce stress in plants. GA has a crucial role in defending plants against oxidative stress, which is frequently brought up by various environmental stressors (Nian et al., 2024).Gallic acid has been demonstrated to enhance the overall antioxidant activity of plants by scavenging free radicals. Furthermore, GA by strengthening both enzymatic as well as non-enzymatic antioxidant mechanisms,and phenolic content of legumes such as Glycinemax, Cicer arietinum, Lens culinaris, Vigna radiata,increased resistance to oxidative stress (Singhet al., 2017). GA improve stress tolerance in legumes across a range of environmental stress situations by affecting various process which is discussed.

Gallic acid (3,4,5-trihydroxybenzoic acid) is produced in plants through shikimatepathways which is an important process for the production of secondary metabolites (Marchiosi et al.,2020). Three biosynthetic pathways have been postulated for plants to produce gallic acid,which includes; (i) 3,4,5-Trihydroxycinnamic Acid β-Oxidation (this process turns derivatives of cinnamic acid into gallic acid), (ii)the hydroxylation of protocatechuic acid results in the formation of gallic acid, (iii) and the most likely route is the dehydrogenation of 3-dehydroshikimic acid, which directly converts the compound to GA (Wawrzyniak et al., 2023). The synthesis of GA occurs in cytoplasm of plants which, is also the place for shikimate pathway.GA iswidely distributed in a number of plants that contains highertannin content, such as Terminalia chebula, sumac (Rhus coriaria), oak species, etc(Sarkar et al., 2015).

Biosynthesis of GA in plants requires two fundamental molecules i.e.(a) erythrose-4-phosphate (E4P-by product of pentose phosphate pathway) and (b) phosphoenolpyruvate (PEP- obtained from glycolysis) (Shende et al., 2024). After the combination of both the molecules by the help of enzyme DAHP (3-deoxy-D-arabino-heptulosonate-7-phosphate) synthasewhich results in the production of DAHP, as displayed in Figure 1 (Maeda andDudareva,2017). Thereafter, DAHP undergoes number of dehydration and reduction processes which includes the involvement of enzymes DAHP dehydratase and shikimate dehydrogenase and thereby, produces shikimic acid (Chenand Ma,2019).The next step in the biosynthesis pathway of GA is the synthesis of chorismite, which is akey branching point for the production of aromatic metabolites, is accelerated by3-dehydroshikimic acid and 3-dehydroquinic acid. The next step in this process is conversion of shikimic acid to chorismite which requires the involvement of two enzymes; shikimate kinase and chorismite mutase.Chrosimite is a critical molecule which is responsible for biosynthesisof diverse phenolic compounds (Nour-Eldinand Halkier, 2017). The conversion of Chorismite to 3-dehydroshikimic acid needs the multiple set of chemical reaction, which further gets converted into protocatechuic acid(Tanand McNeil,2015). All these steps make a preparatory phase for the last step of hydroxylation of protocatechuic acid which adds a second hydroxyl group to its benzene ring at fifth position (Jiaand Liu, 2017). This step is crucial for the biosynthesis of GA and which is further catalysed by hydroxylases or oxidase enzymes.

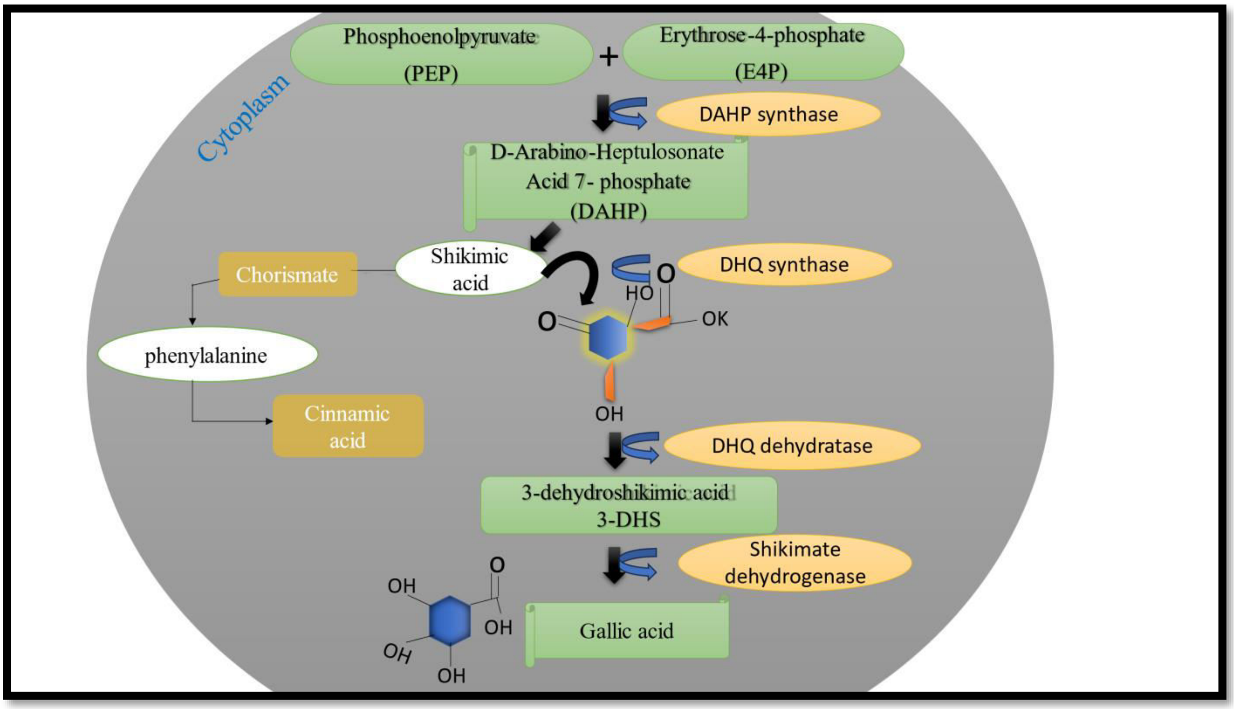

Figure 1: The mechanism of biosynthesis of gallic acid in plants

Role of GA in legumes

Gallic acid is a potential phenolic compound having the ability to support a number of physiological, biochemical and molecular responses in legume plants under stressed environment (Figure 2). The role of gallic acid in alleviating the negative effects of abiotic stressors on legumes discussed in detail, below

Germination, growth and photosynthesis

Seed germination is a process which consist of synchronized events of various physiological and biochemical activities (Nonogaki, 2019). However, various abiotic stressors can hamper the germination and seedling growth of crop plants, including legumes. Gallic acid has been reported to negate the effect of abiotic factors on seed germination, emergence,vigorindex, etc.(Muzaffaret al.,2012; Babaei et al.,2022).Research indicates that GA raises the amounts of chlorophyll and other vital substances that support seed germination and early growth in response to oxidative stress. It also protects seeds under stress during germination by scavenging ROS (NandakumarandRangaswamy,1985).For example, addition of GA in soybean enhanced the amounts of lactic acid, amino acids, and tannin (total phenol and HT), while decreased the pH value, which was helpful to influence the bacterial diversity in rhizosphere (Wang et al., 2021). In addition to seed germination, GAplays crucial role in growth and nutrient uptake of plant.Vigna ungiculata L. plant treated with different concentration of gallic acid (100, 150, and 200 ppm) displayed enhanced root and stem length, fresh and dry weights, number of leaves, leaf area and yield(Gharib et al., 2018).The process by which legumes and other plants transform light energy, water, and carbon dioxide into glucose and oxygen is called photosynthesis, and it mostly takes place in the chloroplasts. However, because of their symbiotic interaction with nitrogen-fixing bacteria (Rhizobia) in their root nodules, legumes have special characteristics connected to their photosynthesis (Layzell et al., 1979). According to Metzener et al. (1965)fresh leaves of cowpea (Vigna unguiculata L.) plants when treated with GA displayed increased concentration of photosynthetic pigments (carotenoids, chlorophyllsa and b) and polyphenols) which led to higher photosynthetic performance of the plants. Similarly, application of GA stimulated the growth by improving water status and photosynthetic efficiency of soybean plants under cold stressed conditions (Yildiztugay et al., 2017).

Osmolytes production and antioxidant defense

In legumes, gallic acid is crucial for controlling osmolyte metabolism and stress reactions, especially in the face of abiotic constraints (Sharma et al., 2019). Osmolytes, including glycine betaine, sugars, amino acids, etcare essential for maintaining osmotic balance and protecting the cellular component from damage induced by unfavourableenvironmental conditions (Chaudhuri et al.,2017).GA is known to improve the synthesis of osmo protectants and reduced the oxidative damage to the legumes grown under harsh conditions(Rahman et al., 2022). Moreover, various studies have revealed that GA can reduce the accumulation of ROS and impart cellular homeostasis to the plants (Khorsandi et al., 2020). GA can also regulate the osmotic homeostasis in plants by interacting with various phytohormones through modulating their signaling pathway (FakhrzadandJowkar, 2023). Besides, GA is an essential molecule which strengthened the antioxidant defense system machinery of legumes under unfavourable circumstances (Mohamed, 2020). GA has the ability to scavenge or neutralised the production of free radical by upregulating the activity of various enzymatic antioxidant enzymes such as POD, CAT, and SOD and non-enzymatic antioxidants which include ascorbate and glutathione, flavonoid etc (Babaei et al., 2022). Moreover, GA can stabilize the membranes and reduce the intensity of oxidative damage by reducing the production of MDA (malondialdehyde), H_2O_2 (hydrogen peroxide), superoxide radical etc(Kumar et al., 2021). Soyabean plants treated with GA displayed higher activity of antioxidative enzymes such as CAT, SOD, GPX, APX etc under salt stressed condition(Menzi, 2017). According to Zhang et al.(2020), when multiple legume crops were treated with GA,they displayed theimproved antioxidative potential then the non-treated plant.

Overall, multiple roles of GA at physiological, biochemical levels have been reported in various legumes species which can help the plants to resist the unfavourable environmental conditions. However,further experimental evidences are required to unravel the molecular mechanisms of GA in imparting abiotic stress tolerance to the plants, especially in legumes.

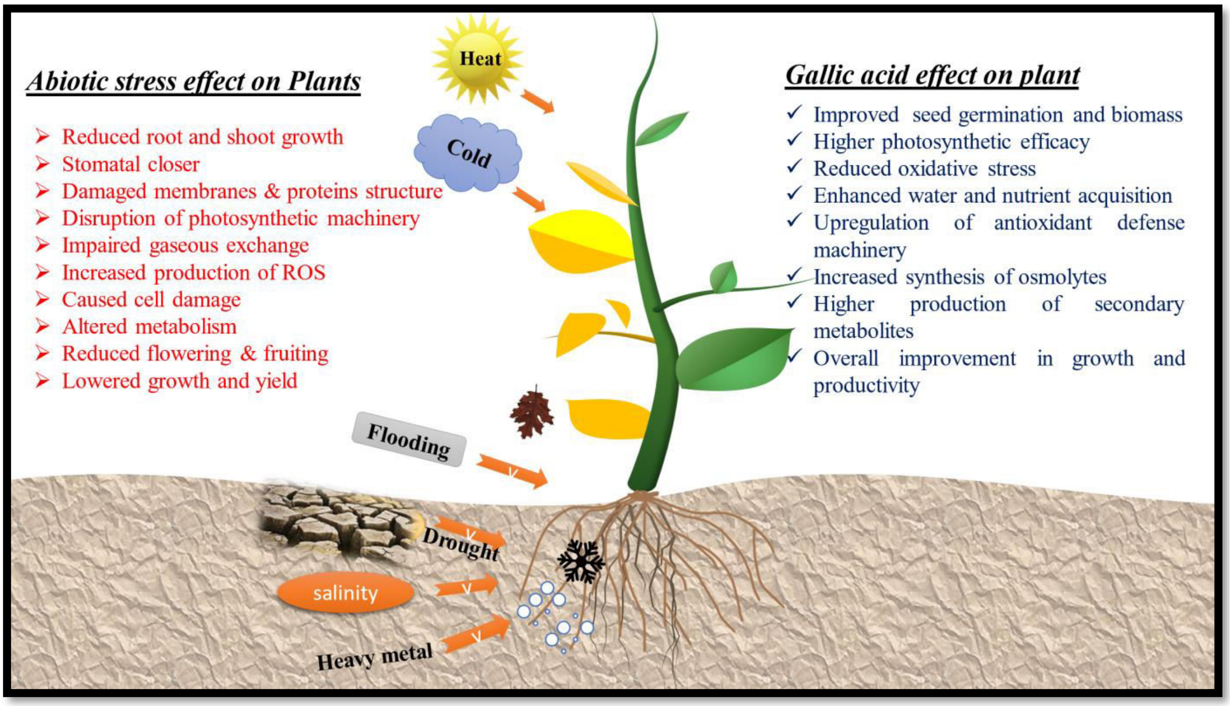

Figure 2: Schematic presentation of role of gallic acid in plants under abiotic stresses

Table 1: Effect of abiotic Stressors on physiological and biochemical responses of different legume species

S.No.	Type of Abiotic stress	Host plant	Effect on legumes	References
1	**Temperature**	Cowpea	Degeneration of the tapetal cells which led to anther indehiscence.	Ahmed et al.1992.
		Soyabean	Reduced growth, water uptake and downregulated the activities of superoxide dismutase (SOD), peroxidase (POX), or catalase (CAT).	Ozfidan-Konakci et al. (2019)
		Peanut	Reduced pollen viability	Zoong et al. (2020)
		Common bean	Sterile pollen grains and indehiscent anther	Gross et al. (1994).

		Common bean	Deteriorated tapetal cells	Suzuki et al. (2001).
		Groundnut	Reduced production of pollen grains	Prasad et al. (1999)
		Soyabean	Decreased pollen germination rate	Djanaguiraman et al. (2013)
		Soyabean	Reduced size of pollen grains	Koti et al. (2005)
		Mung bean	Inhibited the vegetative and reproductive growth.	Kumar et al. (2011)
2.	**Drought**	Chickpea	Reduced plant growth and seed germination rate.	Shariati et al. (2015)
		Soyabean	Reduced shoot biomass accumulation, seed yield, photosynthetic efficiency, water-use efficiency and increased oxidative stress	Princeet al. (2016)
		Common bean	Reduced the growth of belowground parts	Polania et al. (2017)
		Faba bean	Declined growth, shoot and root biomass	Belachew et al. (2018)
		Mung bean	Decreased growth, yield and altered physiological as well as biochemical responses	Ahmad et al. (2015)
		Soyabean	Reduced oil and protein content, disruption of physiochemical and biochemical	Ghassemi-Golezani et al. (2010)

			attributes	
3.	**Salinity**	Faba bean	Declined germination traits, altered starch metabolism, increased oxidative damage and reduced accumulation of osmoprotectant	Bouazzi et al. (2024)
		Faba bean, lentil, Chickpea,Soybean	Reduced germination rate, higher oxidative damage, lowered osmolytes production and antioxidant enzymes activity	Tlahig et al. (2021)
		Mung bean	Decreased height, leaf area, productivity, disrupted chloroplast function and nutrient imbalance	Sehrawat et al. (2015)
		Pea	Decreased growth, photosynthesis, yield attributes and higher oxidative stress	Ali et al. (2015).
		Peanut	Growth was inhibited. Photosynthesis and chlorophyll content declined. Oxidative damage occurred.	Banavath et al. (2018)

		Groundnut	Reduced seed germination, seedling growth, photosynthetic attributes and yield production	Moulick et al. (2020)
		Black gram	Declined growth, productivity and led to ionic imbalance	Moulick et al. (2020)
		Common bean	Reduced growth, impaired photosynthesis, stomatal closure, increased ROS production	Aldoobie et al. (2013).
4	**Heavy metal** (lead, chromium, nickel, cadmium, zinc)	Soybean	Reduced growth and development, nodulation potential, and degradation of chlorophyll	Chen et al. (2003)
	Cadmium	Soyabean	Decreased biomass, yield, photosynthetic rate, and chlorophyll content	Koti et al. (2007)
	Cadmium	Pigeonpea	Reduced growth, yield, photosynthetic pigment concentration rhizospheric enzymatic activity and modulated	Bisht and Garg (2022a, b)

			carbohydrate metabolism	
5.	**UV stress**	Cowpea, Soyabean, Common bean	Higher negative impact om cowpea than common beans and soybeans	Chimphango et al. (2003)
		Pea	Higher oxidative stress, disrupted nitrogen metabolism and hormonal imbalance	Choudhary et al. (2014)
		Chickpea	Reduced growth, nodulation potential and altered N metabolism	Rajendiran et al. (2006)

Conclusion

GA plays a promising role in reducing the negative impact of various abiotic stressors (drought, heat, heavy metal etc.)especially, in agriculturally important crops. All these stressors can hamper the growth and productivity of plants by altering various physiological processes such as inhibition of seed germination, water and nutrient uptake, photosynthesis and induction of oxidative damage. Nowadays, GA is being exploited as a potent molecule which can minimizes the oxidative stress, improves nutrient uptake and photosynthetic ability maintains membrane integrity, and imparts osmotic equilibrium to the plants under unfavourable environments. Moreover, GA strengthens theantioxidant defence system and maintains the oxidative balance in the plants by modulating the expression of various genes. Keeping this in mind, application of GA as astress ameliorative strategy could significantly enhance the growth and yielding potential of legumes under changing environmental conditions, in a sustainable manner. Although, the present study highlights the effect of different abiotic stressors on legumes however, the literature on the specific effects of GA on various legume species undera particular abiotic stressor is limited. Therefore, further investigation is required to unveil the molecular mechanisms behind the action of GA to optimizeits application and assess its effectivity under realistic field conditions.

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