ACTA SCIENTIAE

ISSN: 2178-7727

Role of antioxidant enzymes for various economic crops under fluoride stress conditions with impact on sustainable development of the society

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ABSTRACT

Fluoride, a common ion in the environment is hazardous to all living beings, when exposed in excess concentration. Plants exposed to fluoride over an extended period of time experience changes in their physiological characteristics, biochemistry, and molecular make up. Fluoride induced oxidative stress decreases germination, damages structure of organelles like mitochondrial and chloroplast, affects membrane permeability to ions, disturbs electrolyte balance, and reduces photosynthetic efficiency, all of which affect plant growth, biomass, and production. New approaches to ameliorate fluoride stress impact in plants have been explored in the recent study. Genetic engineering of genes has proven to be an effective strategy for fighting abiotic stress. Such genetic engineering provokes certain pathways with regard to abiotic stress tolerance, and this allows for the generation of stress-tolerant crop varieties that was not possible with traditional breeding methods. This article examines the effects of fluoride induced stress, on the physiological and biochemical indices, antioxidant enzyme activity as well as the amelioration strategies used. Several genetically engineered plants against broad spectrum abiotic stress. These mitigation approaches, essential for overcoming extreme stress situations. Crops that are fluoride stress tolerant and resistant can be designed in the near future with the use of antioxidant enzymes, helping to increase crop production

KEYWORDS: Abiotic stress, Fluoride, Antioxidant defence, Genetic engineering, antioxidant enzymes

INTRODUCTION

Abiotic stress refers to environmental factors adversely impacting plant growth and productivity, including extreme temperature fluctuations, drought, salinity, heavy metals, and xenobiotic substances (Rao *et al.,* 2025; Gull *et al.,* 2019). Climate change exacerbates these stressors, with important implications for growth, development, and production of plants. It has a major effect on cereals productivity, decrease yields by 50-70% (Kumar, 2020). Rice, wheat, and maize are the prime cereals that are highly susceptible to abiotic stresses (Rane *et al.,* 2021). The impacts of these stresses on crops may differ among species and growth stages (Kumar, 2020).

Fluoride stress being, one of the abiotic stresses, arises when plant take up more fluoride from polluted soil and water (Makete *et al.,* 2022). It stimulates generation of reactive oxygen species (ROS) as a stress response. These highly reactive molecules are capable of cause progressive oxidative damage to proteins, lipids, chlorophyll and nucleic acids. Thus, this necessitates the maintenance of equilibrium between ROS production and their scavenging (Gupta *et al.*, 2009). Fluoride pollution is widely recognised as a significant threat to the biotic components of ecological systems. (Singh and Roy Chaudhary, 2020). It has been discovered that fluoride hinders the movement of water and minerals, the couple is essential for physiological and biochemical processes of plant. Groundwater contaminated with fluoride is commonly used for irrigation in fluoride-

ISSN: 2178-7727

endemic areas, which has a detrimental effect on crops (Singh *et al.*, 2013)

This manuscript endeavours to present an outline of our recent understanding on the physiology and biochemical mechanism, plant reaction to Fluoride induced stress. Special consideration has been given to enzymatic antioxidants, in inducing fluoride stress tolerance.

Uptake and Accumulation of fluoride

Mainly, there are two fundamental ways through which fluoride penetrate into plants. One way of uptake is, fluoride settle on leaves, invade into leaves via stomata and else way, penetrates into roots via passive diffusion from the soil and water (Yadu *et al.*, 2016). The availability, pH, and hybridisation of F in the substrates, along with other elements like Al, Ca, and B, all had an impact on fluoride absorption by plant from soil (Zhang *et al.*, 2013). The majority of the F^- absorbed by the roots was easily transferred to the leaves through the xylem. F^- absorption in the leaves is likely influenced by the xylem loading that occurs in the roots following radial transport (Arnesen, 1997). Additionally, there are several channels or transporters known to be involved in anion efflux to xylem (Zhang *et al.*, 2013). Non-ionic diffusion of hydrogen fluoride (HF) across cellular membranes is another way that fluoride is transported. Compared to the F^- ion, the tiny, neutral molecule of HF travels across cell membranes seven times more quickly. Depending on how F moves from the soil to the roots and subsequently into the shoots, it bioaccumulates differently in the various plant components. It was discovered that the roots had the maximum concentration, whereas the leaves, seeds, and shoots had progressively decreased quantities (Baunthiyal and Ranghar., 2014).

Oxidative stress

Unbalanced ROS production and clearance results in oxidative stress (Jomova *et al.*, 2024). Abiotic stressors such as fluoride cause disruption of cellular homeostasis as well as ROS production. The arousal of the cellular antioxidant defence mechanism, which is dependent on their concentration of ROS inside cellular systems, further mitigates the harmful effects resulting from ROS formation (Sharma and Kaur, 2018). Reactive oxygen species (ROS) are a group of oxygen-based compounds known for their active chemical nature and strong oxidative abilities in both plants and animals. (Xiang *et al.*, 2024). According to Table 1, they are separated into two groups: free radicals and non-radicals. Free radicals include one or more unpaired electrons. When two free radicals exchange their unpaired electrons, non-radical form appear (Ozougwu, 2016). In plants, ROS have two distinct functions: at low concentrations, they serve as signalling molecules that trigger defence mechanisms in response to stress, whereas at high concentrations, they exacerbate cellular impairment. ROS generation leads to peroxidation of lipids, oxidation of proteins, nucleic acid impairment, enzyme inhibition, triggering of the programmed cell death pathway, and eventually cell demise if they persist (Panda and Khan, 2009).

Increased ROS concentration leads to activation of antioxidant defence system, in plants it may be relatively simple to divide into two categories: enzymatic and non-enzymatic antioxidants (Yadu *et al.*, 2016).

Table 1- Common ROS produced in living beings (Adapted from Ozougwu, 2016).

Free radical ROS	Non-free radical ROS
Hydroxyl radical (OH^+)	Hydrogen peroxide (H_2O_2)
Superoxide radical (O_2^+)	Singlet oxygen ($^1O_2$)
Nitric oxide radical (NO^+)	Ozone (O_3)
Peroxyl ($RO_2^{\cdot}$)	Hypochlorous acid (HOCl)
Alkoxyl ($RO^{\cdot}$)	
Hydroperoxyl ($HO_2^{\cdot}$)	

Examples of enzymatic antioxidants include glutathione reductase (GR), monodehydroascorbate reductase (MDHAR), glutathione-S-transferase (GST), ascorbate peroxidase (APX), guaiacol peroxidase (POX), superoxide dismutase (SOD), catalase (CAT), and dehydroascorbate reductase (DHAR). Non-enzymatic

ISSN: 2178-7727

antioxidants include ascorbic acid (AA), glutathione, proline (Pro), tocopherol, and flavonoids (Rajput *et al.*, 2021).

Several investigations confirmed that antioxidant defence system combats oxidative stress induced by abiotic stressors like UV-B radiation and heat in *Vigna radiata L.* (Gamit *et al.*, 2025); metal stress such as cadmium(cd) in *Vigna radiata L.* (Anjum *et al.*, 2011), aluminum in *Hordeum vulgaris* (Dawood *et al.*, 2022), Chromium in *Vigna mungo* (Rath and Das, 2020) and non-metal such as fluoride in *Trigonella foenum-graecum* L. (Bhati *et al.*, 2024); drought in *Vigna radiata L.* (Anjum *et al.*, 2015); Salinity in *Vicia faba* beans (Benmoussa *et al.*, 2022). Research conducted on SOD and CAT, their structure, isoforms and activity in various plants under fluoride is discussed in next section.

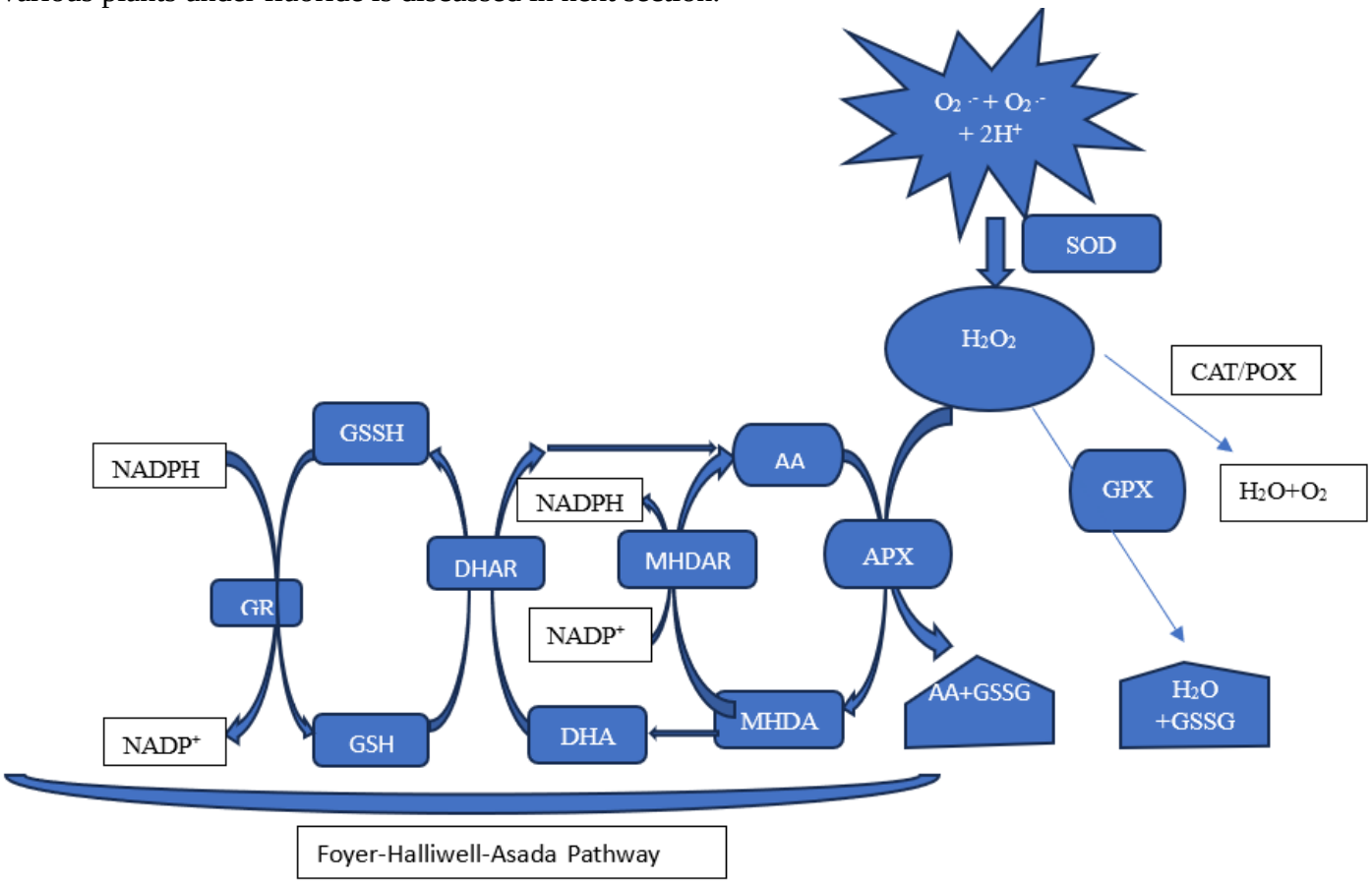

Fig. 2. The chain reaction of actions of intracellular antioxidant enzymes to remove the superoxide anion. (Adapted from Sachdev *et al.*, 2021; Gill and Tuteja, 2010).

Antioxidant enzymes

Because of their sedentary existence, plants have evolved a sophisticated gridded antioxidant defence system that includes several enzyme components and is essential for resisting a variety of stressors (Rajput *et al.*, 2021). These plant enzymes, which are primarily parts of the antioxidant defence system as mentioned previously. SODs, CAT, and POX work together in a variety of ways. CAT and POX protect SODs from H_2O_2 inactivation, whereas SODs protect CAT and POX from O_2^- inhibition.

Moreover, SODs, CAT, and POX prevent the production of OH by removing O_2^- and H_2O_2. This is because, in the presence of iron complexes, O_2^- and H_2O_2 may react to form OH* (Rabinowitch and Fridovich, 1983). The reaction engaged are likely:

Reaction-1 $Fe(III) + O^{2-} \rightarrow Fe(II) + O_2$

Reaction-2 $Fe(II) + H_2O_2 \rightarrow 3\ Fe\ (III) + OH^- + OH^{\cdot}$

Overall reaction- $O^{2-} + H_2O_2 \xrightarrow{Fe(11))} O_2 + OH^- + OH^{\cdot}$ (Haber Weiss reaction)

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Together, these enzymes create a sophisticated system that effectively reduce, eliminate and maintain equilibrium of ROS. In plants, the antioxidant enzymatic components are engaged in either hindering the Haber-Weiss reaction or the Foyer-Halliwell-Asada route, which lowers H_2O_2 and uses the reducing potential of NADPH (Rajput *et al.*, 2021).

Superoxidase dismutase (SOD; EC 1.15.1.1): Types and location

In 1969, Irwin Fridovich and Joe McCord discovered the enzyme SOD in bovine red blood cells. With a very high second order rate constant (k_2 = 2.0 x 10^9 M^{-1} s^{-1}), they showed that this enzyme catalyses disproportionation of superoxide radicals into molecular oxygen and hydrogen peroxide in the reaction described below (Jomova *et al.*, 2024).

Reaction: $O_2^{\cdot-} + O_2^{\cdot-} + 2H^+ \rightarrow 2H_2O_2 + O_2$

SODs are classified into three types depending on the metal co-factors and subcellular localization; copper/zinc SOD (Cu/Zn-SOD), manganese SOD (Mn-SOD), and iron SOD (Fe-SOD). Since O^{2-} cannot traverse membrane, thus must be addressed at their sites of synthesis. Consequently, these enzymes are dispersed throughout various subcellular regions.

In higher plants cytosol, mitochondrial matrix, and plastids have been shown to have Fe-SOD, Mn-SOD, and Cu/Zn-SOD, respectively (Ray chaudhari and Deng, 2000; Bowler et al, 1994). Cu/Zn-SOD is an extracellularly localised homo-dimeric glycoprotein, with each monomer comprises one Cu and one Zn atom and molecular weight varies from 14 to 33 kDa. Mn-SOD, a homo-tetrameric isoform, mainly found in the matrix and inner membrane of mitochondria (Stephenie *et al.*, 2020). Fe-SOD is sensitive to H_2O_2 and resistant to KCN, while Mn-SOD is resistant to both inhibitors and Cu/Zn-SOD is sensitive to both (Del rio *et al.*, 2003; Gill and Tuteja, 2010).

In bacteria, various studies have identified another form of SOD termed nickel SODs (Ni-SODs) utilising nickel as a metal cofactor (Berwal and Ram, 2018). It was initially discovered in *Streptomyces*. There are probable NiSOD genes in various bacterial families and a possible NiSOD fusion gene in *Ostreococcus tauri*, the smallest known free-living eukaryotic green algae. The NiSODs are homo-hexamers of four-helix bundles of molecular weight of about 80 kDa. Nevertheless, they discovered that NiSODs are not present in gram-positive bacteria, archaea or eukaryotes apart from previously mentioned the green alga (Miller, 2012).

Response of SOD to fluoride stress

Studies on various crops show that fluoride exposure generally increases SOD activity as an adaptive response to mitigate reactive oxygen species damage. In the paddy grains, SOD activity (unit/mg protein/min) was raised by 75% over the control value. SOD activity may have risen due to higher metabolic activity or a faster rate of SOD production under the impact of F exposure (Chakrabarti and Patra, 2015). With increasing concentrations of F in the irrigation water, SOD activity increased in all regions of the four plant species (Mustard, Radish, Coriander, Spinach) investigated (Chakrabarti and Patra, 2013). Similar findings were obtained with increased F concentration in Olive plants (Zouari *et al.*, 2017), *Vigna radiata* and *Vigna mungo* (Singh *et al.*, 2021), and *Spirodela polyrhiza* (Sharma and Kaur, 2019), six oat cultivars (Mishra *et al.*, 2024). This increased activity might be an adaptive response to changes in oxidative stress, acting as a positive feedback loop (Chakrabarti and Patra, 2015). However, in tea plants, SOD activity decreased with increasing fluoride concentrations (Li *et al.*, 2011).

Catalase (EC 1.11.1.6): Types and location

Catalases are oxidoreductase enzymes that is present in all organisms (Takio *et al.*, 2021). In 1818, Thenard made the first discovery of catalase activity in plant and animal cells. The identity of catalase was confirmed by Sumner and Dounce in 1937 after it was first isolated and crystallised from beef liver (Scandalios *et al.*, 1990). Catalase serves a central role for preserving the equilibrium of cellular hydrogen peroxide. In both healthy and stressed plants, catalase scavenges H_2O_2 produced by fatty acid oxidation, mitochondrial electron transport, and most importantly photorespiratory oxidation (Xiang *et al.*, 2024).

ISSN: 2178-7727

Catalase has highly ordered three-dimensional configuration. The tetrameric structure of the enzyme is shaped like a dumbbell, consists of four identical monomeric subunits that range in size from 220 to 350 KDa. Each tetrameric subunit folds to form four distinct structural domains: the wrapping loop, the β-barrel domain, the N-terminal, and the α-helix area/ C-terminal (Glorieux and Calderon, 2017; Takio *et al.*,2021; Dwivedi *et al.*, 2016). Each monomer unit contains a heme, a prosthetic group made up of a core iron atom joined by a protoporphyrin ring (Sharma and Ahmad, 2014).

H_2O_2 initially oxidises the iron in the CAT to produce an intermediate iron peroxide. The enzyme can remain in this resting state if the H_2O_2 concentration is low. Conversely, the second H_2O_2 molecule functions as a reductant for this intermediate iron peroxide at higher H_2O_2 concentrations, which regenerates the enzyme and releases oxygen and water in the second step (Rajput *et al.*, 2021). Catalase has one of the highest turnover rates among all the antioxidant enzymes. One catalase molecule has the capacity to convert six million H_2O_2 molecules into H_2O and O_2 every minute (Feierabend, 2005).

Step 1: CAT-Fe-OH + H_2O_2 → CAT-Fe-OOH + H_2O
Step 2: CAT-Fe-OOH + H_2O_2 → CAT-Fe-OH + H_2O + O_2

In higher plants, Catalase may be categorised into three primary types, in conformity with prosthetic groups, sequences, quaternary structures, and subunit sizes: I stand for monofunctional catalases, II for bifunctional catalase peroxidases, and III for nonheme catalases (Loewen *et al.*, 2002). CAT 1 is abundantly expressed in photosynthetic tissue and primarily participates in scavenging photorespiratory H_2O_2. The physiological function of CAT2, which is primarily expressed in vascular tissue, is yet unknown. Seeds and young plants contain CAT 3, which is associated with glyoxysomal activity (Almeida *et al.*, 2005). All known eukaryotic forms of catalase are heme-based, while certain bacterial forms employ manganese as the redox-active co-factor (Mhamdi *et al.*, 2010).

It has been reported that there are many catalase isoforms that are encoded by distinct genes (Cat1, Cat2, Cat3) and expressed in organelles in ways that are unique to time and length of stress (Sharma and Ahmad, 2014; Mhamdi *et al.*, 2010). Three isoforms of CAT have been identified in *Nicotiana tabacum* (Havir *et al.*, 1996), Arabidopsis, Maize, Pumpkin and Rice (Mhamdi *et al.*, 2010). One possible explanation for the existence of many peroxisomal isoforms made up of subunits with the same molecular mass is posttranslational modification. The occurrence of many potential oxidation states of the enzyme, consequently, heme group alterations may account for the presence of multiple catalase conformers (Corpas *et al.*, 1999).

Effect of Fluoride on CAT activity

CAT activity may rise or fall in response to oxidative stress, depending on the type, intensity, and length of the stress. Several scaled research corresponds with catalase activity against F-stress response is as follows- three aquatic macrophytes, including *Pistia stratiotes*, *Eichhornia crassipes*, and *S. polyrhiza*, were similarly shown to have elevated catalase activity (Karmakar *et al.*, 2016). In *S. polyrhiza* under fluoride stress, CAT activity was shown to be considerably higher at a high concentration compared to control (Sharma and Kaur *et al.*, 2019). CAT activity was reduced in maize (Mutahir *et al.*, 2016) and tea plants at high concentrations of fluoride, whereas it had maximum activity at moderate concentrations in tea and mung bean (Li *et al.*, 2011).

Effect of fluoride on Physiological and biochemical parameters of Plants

For plants, F is not regarded as an important ingredient. In general, F can alter or interfere with plant metabolism. The majority of plants are susceptible to F (Pelc *et al.*, 2017).

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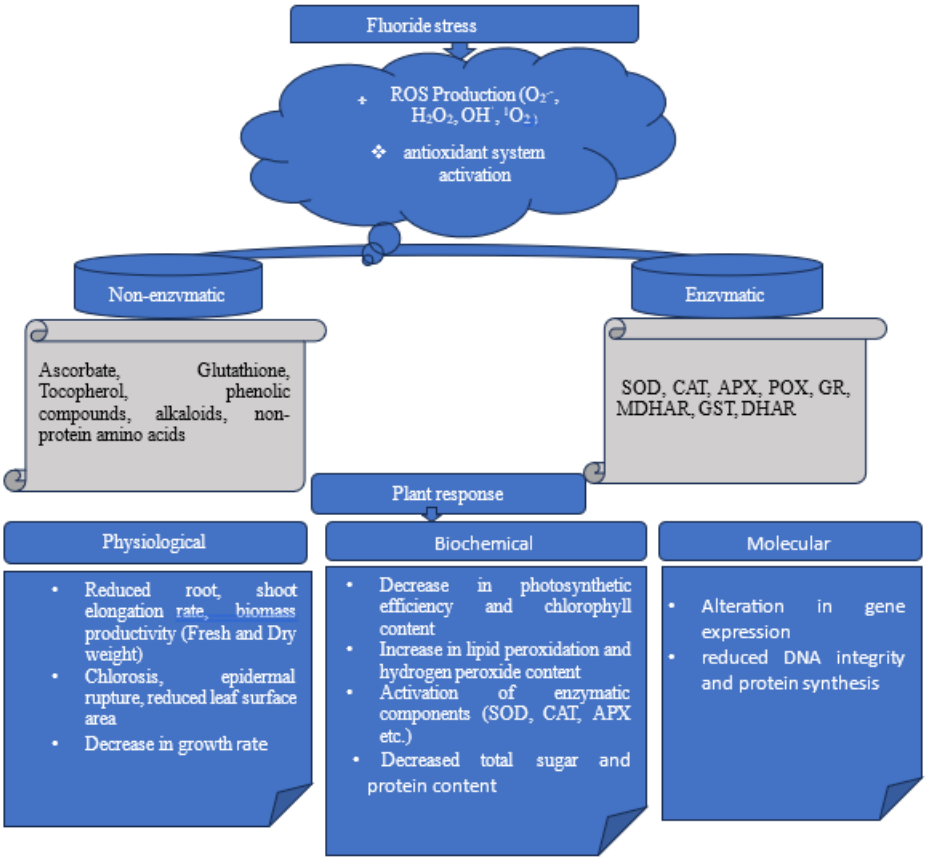

Fig-1; Effect of Fluoride stress antioxidant defence system (Gill and Tuteja, 2010; Yadu *et al.*, 2016; Sharma and Kaur, 2018).

Beginning with germination and the early growth of seedlings, fluoride toxicity impacts most morphological, physiological, and biochemical characteristics of plants without causing obvious harm, even at very low ambient concentrations (Panda, 2015; Pelc *et al.*, 2017). Numerous physiological functions, such as root and shoot length, fresh weight, dry weight, sprouting, mineral nutrition, membrane permeability, respiration, photosynthesis, translation, carbohydrate metabolism and lipid peroxidation, are negatively affected by fluoride, thereby affect development, plant matter, and yield (Singh *et al.*, 2013; Panda, 2015; Pelc *et al.*, 2017). The physiological parameters and the quantitative changes, in a number of biochemical parameters, including the MDA content, ascorbate, proline, flavonoids, polyphenols, hydrogen peroxide, glutamate, and photosynthetic pigments (carotenoids and chlorophylls) were monitored using established methods in numerous studies such as *Oryza sativa* (Banerjee *et al.*, 2019), *Macrotyloma Uniflorum* (Singh *et al.*, 2025)**,** *Vigna spp*. (Singh *et al.*, 2021), *Oryza sativa* varieties (Singh *et al.*, 2025), *Cicer arietinum* and *Hordeum vulgare L*. (Sachan and Lal, 2018), *Spirodela polyrhiza* (Sharma and Kaur, 2019), *Withania sominfera L*. (Yadav *et al.*, 2024), *Trigonella foenum-graecum* (Burgohain and Chowdhwara, 2022), *Phaseolus vulgaris* L. (Ahmed *et al.*, 2024), *Triticum aestivum* cultivars (Kumari *et al.*, 2024) and *Abelmoschus esculentus L.* (Ahmed *et al.*, 2019), *Triticum aestivum* (Agarwal and Chauhan, 2014), *Vigna radiata* (Bano *et al.*, 2021), *Pisum sativum L.* (Ahmed *et al.*, 2021), *Cajanus cajan* (Yadu *et al.*, 2018).

Adverse effects of fluoride toxicity on productivity of major cereal crops with different levels of tolerance has also been reported. Wheat was more tolerant than barley at 100 ppm fluoride, but both were equally sensitive at 200 ppm (Singh *et al.*, 2017). Maize and rice both had reduced net primary productivity (NPP) with an increase in fluoride content, with maize being more sensitive (Mishra *et al.*, 2014). Six oat cultivars had lower growth, chlorophyll content, and photosynthetic parameters under fluoride stress (Mishra *et al.*, 2024). Barley, which is more fluoride-tolerant than other cereals, had cultivar-specific reactions. RD2786 had improved adaptation to fluoride stress, having higher alkaloid, carbohydrate, phytosterol, flavonoid, and phenolic content than RD2794 (Sahariya *et al.*, 2021). These observations underscore the contrasting impact of fluoride

ISSN: 2178-7727

stress on cereals and prospects for the determination of tolerant cultivars.

Various approach for amelioration of fluoride stress

New approaches to prevent fluoride stress in plant have been explored in recent study. Bacterial consortia isolated from various sources have been successful in reversing the impact of low levels of the sodium fluoride form on plants like *Vigna radiata* and *Oryza sativa* (Maitra *et al.*, 2013). Plant growth-promoting rhizobacteria (PGPR) have been identified as functional bioremediators with a set of defence mechanisms against fluoride toxicity and enhancing plant tolerance (Singh *et al.*, 2023). Microbial bioremediation processes, including bioaccumulation, biotransformation, and biosorption, have been explored in the context of fluoride removal. But more is needed to engineer the practical implementation of these biological processes at an industrial scale and to develop new process modifications that are capable of enhancing their efficacy in fluoride removal (Kumar *et al.*, 2021).

Table 2- Some experimental findings correlate to oxidative stress mitigation against the F-stress response in crop plants.

Plant	Protector molecule/organism	Effect of protector on different plants under fluoride stress	References
Phaseolus vulgaris L.	Selenium-Nanoparticles	Chl a, Chl b, and carotenoid levels were reduced by 88.8%, 95.5%, and 96%, respectively, by NaF toxicity compared to the control.	Ahmed *et al.*, 2024
Vigna radiata and *Vigna mungo*	Sodium nitroprusside (SNP)	SNP facilitated the synthesis of osmolytes, non-enzymatic antioxidants, and antioxidant enzymes, thereby mitigating the toxic effects of fluoride in both species	Singh *et al.*, 2021
Triticum aestivum	Silicon	silicon exhibited a positive impact on wheat cultivars subjected to fluoride stress and those that were not. Silicon was observed to diminish the levels of malondialdehyde (MDA) and hydrogen peroxide (H_2O_2), while simultaneously enhancing the antioxidant defense mechanisms.	Sogarwal *et al.*, 2025
Oryza sativa L.	*Pseudomonas aeruginosa* (M W843625)	augmented nutrient absorption and increased total chlorophyll, soluble protein, biomass and lower F concentrations in roots, shoots, and grains. Increased antioxidative gene activity (SOD, CAT, and APX) was associated with *P. aeruginosa* inoculation, which led to decreased ROS and MDA levels.	Katiyar *et al.*, 2025
Camellia Sinensis L.	Melatonin	enhance maximum photochemical efficiency of PSII and antioxidant capacities to mitigate fluoride stress.	Ruan *et al.*, 2025

Phytoremediation using Amaranthus hybridus has also been proven to enhance the efficiency of iron (III) salts in defluoridation, likely through root exudates or the charge nature of root surfaces (Kapenja *et al.*, 2017). Plant hyperaccumulators and bioadsorbents offer a promising and economically viable option compared to conventional defluoridation processes, but there is more to be done for commercialization (Sharma *et al.*, 2021).

Corrective soil amendment with calcium carbonate can inhibit fluoride uptake in plants, while the application of phosphorous fertilizers can exacerbate the problem (Stanley *et al.*, 2002). The application of biochar reduces

ISSN: 2178-7727

the solubility and concentration of fluoride in plant tissue, thereby reducing oxidative stress and enhancing safflower seedling growth (Ghassemi-Golezani & Farhangi-Abriz, 2019). Soil management and bioremediation techniques have also been reported to be effective alternatives for the remediation of fluoride pollution in soil-plant ecosystems (Wang *et al.*, 2023). These innovations offer environmentally friendly alternatives to conventional procedures for the alleviation of fluoride stress in plants and the remediation of fluoride-contaminated environments. Genetic engineering also holds promising solutions to the creation of crops tolerant to environmental stresses like drought, salinity, and high and low temperatures (Wang *et al.*, 2003).

Genetic engineering: Approach for developing abiotic stress-tolerant plants

Genetic engineering of genes has proven to be an effective strategy for fighting abiotic stress (Gill *et al.*, 2015). Such genetic engineering provokes certain pathways with regard to abiotic stress tolerance, and this allows for the generation of stress-tolerant crop varieties that was not possible with traditional breeding methods (Jan *et al.*, 2013).

Table 3-Genetic engineering of various genes involved in combating abiotic stress for developing abiotic stress tolerant plants

Gene	Plant /Source/Transgenic	Stress tolerance enhanced	Remarks	References
Cu/Zn-SOD (Cytosolic)	*Avicennia marina* → Transgenic rice	Salt, drought	Enhanced tolerance in transgenic rice	Prashanth *et al.*, 2008
SodERF3 (Ethylene responsive gene)	Sugarcane→ Transgenic plant	Drought, salt	Promising result for abiotic stress tolerance	Ali *et al.*, 2020
Cu/Zn-SOD	*Arachis hypogaea*→ Transgenic tobacco	Drought, salinity	Enhanced tolerance in transgenic Tabacco	Negi *et al.*, 2015
SOD and APX	*Arabidopsis*	Salt	Modulated lignin biosynthesis; improved growth and yield	Shafi *et al.*, 2015
Am-SOD	Indica rice (Sambha mahsuri, Cotton sannalu)	Abiotic stress	Developed via *Agrobacterium tumefaciens* co-culture Developed via *Agrobacterium tumefaciens* co-culture	Reddy *et al.*, 2015
Cu/Zn-SOD and APX	transgenic tall fescue	Broad spectrum Abiotic stress	Enhanced resistance	Lee *et al.*, 2007
Catalase gene (TdCAT1)	Wheat→ Yeast and Arabidopsis	Broad spectrum Abiotic stress	Maintaining growth, proline accumulation, and H_2O_2 alleviation through increased catalase and peroxidase activities	Feki *et al.*, 2015

CONCLUSION

Plants undergo physiological, biochemical, and molecular changes as a result of long-term F exposure. The study reviewed that F- has a physiological influence on plants by shortening root and shoot length, changing

fresh and dry weight. Plant cells contain a range of antioxidants, including both enzymatic and non-enzymatic components, which may protect stressed cells against abiotic stress. The study looked at the activity of three antioxidative enzymes in plants: superoxide dismutase, catalase, and ascorbate peroxidase. SOD catalyses conversion of O^{2-} to H_2O_2 and O_2. SOD activity seen increasing with increase in fluoride concentration. Increase in SOD activity could be because of increased metabolic activity or a quicker rate of SOD generation as a result of F exposure. H_2O_2 can be converted by catalase into H_2O and O_2 under both, normal and stressed scenarios. Its activity increase and decrease according to kind, severity, and duration of the stress. In most of the studies its activity seen to peak at a particular fluoride concentration similar trend have been seen with ascorbate peroxidase enzyme activity. Overall, the review concluded that antioxidant enzymes play an important role to overcome the fluoride stress situations.

FUTURE PROSPECTIVE

In the nearby future, Genetic engineering progress presents future solutions towards enhancing crop productivity under fluctuating climatic conditions. Implementing such genetic modification technologies will be crucial in addressing future challenges in crop productivity under changing climatic conditions. Enhanced crop yield directly affects the income generation of rural communities. So somehow these inventions through Agriculture biotechnology to develop Fluoride tolerant/Resistant crops will help to sustainable development of the society.

ACKNOWLEDGMENT

Sincere gratitude is extended by the authors, to Jayoti Vidyapeeth Women's University in Jaipur, Rajasthan 303122, India, for providing the infrastructure assistance necessary to finish this work.

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