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Salicylic Acid-mediated Salinity Stress and Mercury Toxicity Tolerance: A Comparative Framework for Tulsi (*Ocimum sanctum L.)*

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Abstract

Tulsi (*Ocimum sanctum*) is a medicinally important plant and it is sensitive to environmental stress such as salinity and mercury toxicity. Abiotic stresses like mercury toxicity and salinity adversely affecting the growth of the plant, metabolism and the productivity of the plant by disturbing the physiological and biochemical processes. The salinity stress and mercury toxicity causes severe plant damage in soil leading to ionic imbalance, osmotic stress and formation of reactive oxygen species (ROS), which causes oxidative damage to the cells of the plant. To counter this from the oxidative stress the plant boosts its antioxidant defence system.

Salicylic acid (SA) is a plant growth regulator and signalling molecule and it also regulates the antioxidant enzyme activity by improving the stress adaptation. Salicylic acid plays a role in controlling the salinity and mercury toxicity which induces the oxidative stress and can be an effective method to improve plant tolerance against both the abiotic stress. By using existing literature and bringing together dispersed data and unifying *Ocimum Sanctum* to the broad plant models, this review presents a predictive framework for SA mediated stress tolerance in Tulsi and it underlines the importance of conducting direct empirical evidence on the direct applicability of these deduced pathways on Tulsi to make agriculture more sustainable.

Keywords: *Ocimum sanctum, Salicylic acid, Antioxidant enzymes, Abiotic stress, Salinity stress and Mercury toxicity.*

1. Introduction

Ocimum sanctum is a medicinal plant which is very well known and commonly called as Tulsi or holy basil has been used for its highly antioxidant, antimicrobial, and anti-inflammatory actions since ancient time as it has been valued not only for its healing effect but also for spiritual and religious reason. It is often termed as □queen of herbs□ due to its significant range of health benefits and overall well-being it offers.(Cohen, 2014; Murugan et al., 2025)

Ocimum sanctum possesses naturally diverse bioactive compounds such as flavonoids, alkaloids and phenolic compounds, responsible for its medicinal effects. These compounds are responsible for activating antioxidant, antimicrobic and anti-inflammatory actions and also for activating the immunity system , due to this Tulsi is known for the treatment and management of several health conditions such as respiratory conditions , cough, fever and digestive issues etc.(Cohen, 2014)

One of the main attributes of Tulsi is its antioxidant potential because it has the ability to counter the synthesis of reactive radicals in the body. This property helps in healing of the body from chronic illness and improving immunity. Tulsi helps the body to counter stress and maintain the physiological balance under adverse conditions.

Tulsi plant had always been known for its antimicrobial property against numerous of pathogens, including bacteria, fungi, and viruses. These properties of Tulsi plant make it useful in preventing infections and promoting overall health. In addition to this it has been implicated as a medicinal plant in cardiovascular health, in controlling blood sugar levels, and in overall better liver functions. (Cohen, 2014; Issac Abraham et al., 2024)

Moreover, the therapeutic use of Tulsi has gained attention for its potential role in managing the metabolic disorders. Several studies have indicated that the standard uptake of Tulsi extracts may help in the regulation of blood glucose levels and improving insulin sensitivity. This makes it relevant for the treatment of conditions like diabetes mellitus. Also, the lipid lowering properties contribute in the regulation of cholesterol levels, hence, reducing the risk of cardiovascular diseases.

Plants are regularly subjected to various environmental conditions throughout their life cycle. Since plants are immovable and they cannot avoid the unfavourable environmental conditions and hence they have to develop the adaptive mechanism to survive.

Abiotic stresses such as drought, salinity, extreme temperature and heavy metal toxicity severely affect plant growth, physiology and productivity. (Akula & Ravishankar, 2011; Emamverdian et al., 2020; Nowicki et al., 2025)

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Salinity stress mainly occurs due to greater amount of sodium chloride (NaCl) present in the soil. Due to this increased concentration of NaCl in the soil, it limits the uptake of water from the plant roots. Rise in the amount of NaCl in the plant cell disturbs the ion uptake which leads to osmotic imbalance and disrupts nutrients uptake. (Genc et al., 2019; Misra & Saxena, 2009; Sahoo & Tuteja, 2013) Mercury toxicity affects plants at physiological, biochemical, and molecular levels. Mercury interferes with photosynthesis, respiration, water balance, nutrient uptake, and in the stability of the membrane. (Abbasi et al., 2023; Agarwal et al., 2025; Ýþkil et al., 2022) Salinity and Mercury stress causes toxic effects in organisms through its ability to create oxidative stress conditions. The condition of oxidative stress arises when plants produce reactive oxygen species at a level that exceeds their capacity to defend against these substances.(Birben et al., 2012; P. Sharma et al., 2007) In view of the rising problem of soil salinity and mercury toxicity and the medicinal importance of Tulsi, it is important to evaluate ways to improve its tolerance to salinity stress and mercury toxicity. Salicylic acid has shown ability to enhance plant stress tolerance.(Chen et al., 2009; Emamverdian et al., 2020; Khan et al., 2015) as a result, this review targets to evaluate the contribution of salicylic acid in *Ocimum sanctum* under salinity stress and mercury toxicity.

Multiple studies have reported that abiotic stress significantly reduces the growth parameters such as length of the shoot, length of the root, weight of fresh parts of the plant, weight of dry part of the plants. Salicylic acid can alleviate the adverse impact of the abiotic stress in the plants.(Akula & Ravishankar, 2011; Emamverdian et al., 2020; Khan et al., 2015) Salicylic acid treatment has been reported to enhance antioxidant enzyme activities, reduce lipid peroxidation, and maintain better photosynthetic efficiency under salinity stress and mercury toxicity stress conditions. It helps regulate ion balance thereby reducing ionic toxicity.(Abdi et al., 2022; Mahgoub et al., 2025; Rithichai et al., 2024)

2. Methodology and literature search strategy

We systematically searched scientific literature to assess the independent and interactive effects of salinity stress and heavy metal (mercury) toxicity on different plant species, as well as the role of SA in mitigating stress responses**.**

2.1 Search databases and scope

The literature search was carried out in prominent indexing databases (PubMed, ScienceDirect, Google Scholar), with supplementary manual filtering of high-impact plant science journals. We considered a wide range of plant models, covering agricultural crops (e.g., *Triticum aestivum, Oryza sativa* etc), and medicinal plants (e.g., *Catharanthus roseus*, *moringa oleifera* etc), aiming to map the broad physiological and biochemical responses. Peer-reviewed publications were included since 2006 till July 2026.

2.2 Search terms and keywords

The search utilized combinations of Boolean operators (AND/OR) with the following keywords and phrases:

("Plant model", OR "crop plant" OR "medicinal plants")

AND ("salinity stress" OR "salt stress")

AND ("mercury toxicity" OR "SA")

AND ("Abiotic stress" OR "oxidative stress")

2.3 Inclusion criteria

Peer-reviewed, original research articles and critical reviews demonstrating the effect of salt stress or mercury toxicity on the physiological, biochemical or molecular aspects of plants. Research related to salicylic acid-mediated protection of antioxidant enzymes, osmotic adjustment or photosynthetic ability under these stress conditions. All plant species are considered to facilitate comparison between different stress mitigation pathways.

3. Salicylic Acid in Plant Stress Tolerance

Salicylic acid (SA) also called as 2-hydroxybenzoic acid is a phenolic compound which acts as an important signalling molecule in plants. (An & Mou, 2011; Maruri-López et al., 2019) SA is well known for developing systemic acquired resistance (SAR) towards the pathogens and also involved in altering the responses to abiotic stresses.

Salinity stress often inhibits the photosynthetic rates because of the stomatal closure and reduced chlorophyll content. Salicylic acid can also be given exogenously and it has shown to mitigate the effects by improving the chlorophyll concentration and photosynthetic efficiency, leading to better growth under the influence of stress. (Abdi et al., 2022; Emamverdian et al., 2020; Misra & Saxena, 2009) 2-hydroxybenzoic acid helps in the enhancement of antioxidant defence which limits the damage by the oxidation and improves the growth of the plant under the stress conditions.(Birben et al., 2012; Issac Abraham et al., 2024; Rithichai et al., 2024; P. Sharma et al., 2007) Nonetheless the extent of SA regarding the protection provided by the salicylic acid towards the stress varies among plant species and goverened by the conditions such as concentration , method of application , and duration of stress exposure.

Salicylic acid also influences osmotic balance by increasing Osmotic compounds such as soluble sugars and proline which helps in managing the cell turgor and safeguard cellular structure under salinity stress.(Genc et al., 2019; Misra & Saxena, 2009; Sahoo & Tuteja, 2013)

The most widely observed effect of SA under abiotic stress is the enhancement of antioxidant enzyme activities. SA treatment has been shown to increase the response of radicle scavenging enzymes in various plant species under abiotic stress, suggesting an improved capacity to neutralize the ROS. SA elevates the antioxidant defences, stabilizes membranes, improves osmotic

adjustment, and can also regulate the ion transport systems. It also brings the upregulation of stress-responsive genes and may interact with other hormonal pathways to coordinate a systemic stress response. (Chen et al., 2009; Emamverdian et al., 2020; Wani et al., 2017)These combined effects help to reduce the harmful impact of salinity stress and mercury toxicity on physiological and biochemical activities of the plants.

4. Effects of Abiotic Stress on *Ocimum sanctum*

The growth and the metabolism of plants are affected as they constantly face environmental challenges. Among these, salinity stress and mercury toxicity are particularly harmful because both interfere with physiological processes and trigger oxidative damage within plant cells. In medicinal plants such as *Ocimum sanctum* (Tulsi), these stresses not only reduce growth and biomass but can also alter the production of valuable secondary metabolites. Understanding how these stresses affect the plant is essential before exploring the protective role of salicylic acid and antioxidant defence mechanisms.(Akula & Ravishankar, 2011; Khan et al., 2015; Nowicki et al., 2025)

5. Mercury Toxicity

5.1 Sources of Mercury Contamination

In the external environment, Mercury (Hg) is one of the severely toxic heavy metals present. It enters agricultural soils through industrial waste, mining activities, coal combustion, pesticides, fertilizers and contaminated irrigation water as mercury is non-biodegradable, it accumulates in soil over time and becomes available for uptake by plants through their roots. Several cellular processes experience physiological and biological disturbances due to mercury interference.(Ýþkil et al., 2022; Rafati-Rahimzadeh et al., 2014; Unsal, 2018)

5.2 Effect of Mercury Toxicity on Plant Growth

Almost every stage of plant development is affected by mercury toxicity. Exposure to mercury reduces seed germination, inhibits the growth of the root and shoot, decreases in the area of the leaf, and lowers overall organic matter production. One of the primary reasons for growth inhibition is the disruption of nutrient and water uptake by roots.

Mercury also damages chloroplasts and reduces chlorophyll content, leading to impaired photosynthesis. As photosynthetic efficiency declines, the plant produces less energy for growth and maintenance. In *Ocimum sanctum*, prolonged mercury exposure may result in stunted growth, yellowing of leaves and reduced medicinal quality.(Abdi et al., 2022; MacDonald & Mohan, 2025; P. Sharma et al., 2007)

5.3 Effect of Mercury Toxicity on Production of Reactive Oxygen Species (ROS)

Mercury toxicity at the cellular level leads to excessive generation of the ROS such as Superoxide radicals (O_2), hydrogen peroxide(H_2O_2) and hydroxyl radicals (OH). ROS are produced in small amounts and function as the signal molecules, normally. However, mercury disturbs cellular metabolism and causes uncontrolled ROS accumulation.

The excessive ROS attacks cellular membranes, proteins, nucleic acids and photosynthetic pigments, resulting in oxidative stress .If not neutralised, oxidative stress can severely damage cellular structures and eventually lead to cell death .(Birben et al., 2012; Khalid et al., 2023; Khan et al., 2015; P. Sharma et al., 2007; Unsal, 2018)

6. Salinity Stress

6.1 Causes of Salinity Stress

Stress due to salinity occurs when high concentrations of soluble salts, mainly sodium chloride (NaCl), build up in the soil. This problem is increasingly common in the arid and semi-arid regions due to lack of the proper irrigation practices, inadequate drainage systems and high evaporation.

The presence of excess salts around plant roots creates unfavourable conditions for water absorption and disrupts normal cellular functions.(Genc et al., 2019; Hussain et al., 2018; Ko et al., 2007; Misra & Saxena, 2009; Sahoo & Tuteja, 2013)

6.2 Osmotic Stress

Osmotic stress is the first effect of salinity. High salt concentrations in the soil decreases the water potential, making it hard for the roots to soak up the water. Although water may be present on the soil, the plant experiences physiological drought because it cannot access it efficiently.

As a result, cells lose turgor pressure, stomata close to reduce water loss, photosynthesis decreases and overall plant growth slows down. Symptoms such as wilting, reduced leaf expansion, and poor biomass accumulation commonly occur under osmotic stress.(Babu & Uma Maheswari, 2006; Chen et al., 2009; MacDonald & Mohan, 2025)

Among the enzymatic antioxidants, Superoxide Dismutase (SOD), Catalase (CAT) and Peroxidase (POD) play particularly important roles. These enzymes act as the first line of defence against ROS accumulation and help the plants survive under stressful environmental conditions.(De Los Reyes et al., 2003; Hussain et al., 2018; A. Sharma et al., 2020a; P. Sharma et al., 2007)

6.3 Ion Imbalance Toxicity

Besides osmotic impact, intracellular excess buildup of sodium and chloride ions in plant tissues also causes ionic toxicity. Excess sodium (Na^+) competes with important nutrients such as potassium, calcium and magnesium upsetting the intracellular nutrient balance. Potassium plays a vital role in enzyme activity, and stomatal regulation. The cellular replacement of potassium with

sodium brings about impairment in many metabolic activities of the plant cells including its growth, photosynthesis, protein synthesis and cellular metabolism. The salinity also like mercury stress produces excess ROS and results in the oxidative damages(De Los Reyes et al., 2003; Khalid et al., 2023; Mahgoub et al., 2025; Sahoo & Tuteja, 2013; Unsal, 2018)

6.4 Osmolyte Accumulation and Phytohormonal Signalling Crosstalk under Salinity Stress and Mercury Toxicity

Salinity results in osmotic shock whereas, mercury (Hg) toxicity leads to cellular metabolism malfunctioning. Salicylic Acid (SA) is a potent metabolic enhancer, capable of stimulating and accumulating compatible solutes (osmolytes) for maintenance of turgor pressure and stabilization of macromolecular structure without inhibiting cellular metabolism. Proline metabolism enhanced: SA increases the activity of pyrroline-5-carboxylate synthetase (P5CS), the principal rate limiting enzyme in the process of proline biosynthesis, while at the same time decreases proline dehydrogenase (PDH) activity. (A. Sharma et al., 2020b)

Proline, which is increased by SA application, serves both as an osmolyte in mitigating salinity imposed physiological drought and as a non-enzymic scavenging molecule for free hydroxyl radical caused by heavy metals in *Ocimum sanctum*. (Alam et al., 2022)

Total soluble sugar and glycine betaine content SA enhances total soluble sugar and glycine betaine contents even under combinatorial stress conditions. These solutes have capability of forming hydration shells around important enzymes and stabilization of thylakoid membranes in the chloroplast of Tulsi for protection from chlorosis under toxic mercury concentration.

(Wahab et al., 2022)

SA cannot work as a singular molecule and exists as part of a complex endogenously regulatory network. The ability of SA to protect *Ocimum sanctum* is very dependent on the antagonistic or synergistic crosstalk with additional phytohormones: SA-ABA (Abscisic Acid) Synergy on stomatal regulation; Under high salt condition, SA works in synergic action with the endogenous hormone ABA. While initial stomatal closures due to the ABA/ Ca^{+2} signaling pathway leads to inhibit water loss, SA enhances this response preventing the over-stomatal closing, thereby maintains CO_2 assimilation needed for an optimal production of volatile compounds inside the gland of Tulsi. SA-JA (Jasmonic Acid) interplay under toxic environments; Under heavy metal stress high content of JA tends to promote a necrotic responses via JA signalling, while excessive mercury leads to necrobiosis of plant tissue by favouring JA/ necrosis responses; However exogenous applications of SA reduce the SA/JA antagonism and hence suppresses accelerated PCD of tissues. (Li et al., 2022)

SA also inhibits metal transporters to hinder further uptakes of toxic metals such as Hg^{+2} into the aerial part of the plants. (Gupta & Seth, 2021)SA-Ethylene axis crosstalk on stress induced events; Environmental stress and accumulation of salt & heavy metals in soil may induces an inducible stress ethylene spike thus promotes senescence and leaf falling.

SA interferes and modulates ethylene synthesis and promotes plant longevity by suppressing ACC synthase activity.(Wang et al., 2024)

7. Oxidative Stress and the Antioxidant System

Even though the cause of mercury toxicity and salinity stress are distinct environments, the final physiological impact to the plant cells under both types of stress is the development of oxidative stress. Under these stresses, cell metabolism is dispersed, which consequently results in the overproduction of the ROS. It is known that at some point in mitochondrial electron transport chain electrons leak and will donate a single electron to molecular oxygen, this resulting in $O_2^{\cdot}$. Radical, and then can form H_2O_2 and other ROS, such as OH radical.

When ROS accumulate to levels which exceed the ability of plant's detoxification systems to cope, oxidative stress occurs. As a consequence, excesses ROS have a deleterious effect to plant by damaging membrane lipids causing lipid peroxidation and integrity loss. They also oxidize proteins to form inactivating enzymes, damaging DNA and destroy photosynthesis systems. It can lead to reducing the plant growth, yield and tolerance.

However, plants have a complex defence system against oxidative damage by an antioxidant network which comprises enzymic and non-enzymic antioxidants.(Birben et al., 2012; J. Hussain et al., 2021; Kandimalla et al., 2020; Konkolewska et al., 2020; Singh et al., 2018; Unsal, 2018; Vijayalakshmi et al., 2007)

7.1 Role of Antioxidant Enzymes in Stress Tolerance

To cope with oxidative stress caused by mercury toxicity and salinity, plants activate their antioxidant defence machinery. Antioxidant enzymes function like a cellular protection team, continuously removing harmful reactive oxygen species before they can damage important cellular components. As stress intensity increases, plants generally enhance the activity of these enzymes to maintain cellular homeostasis and improve stress tolerance.

7.1.1 Superoxide Dismutase (SOD)

Superoxide Dismutase is considered as the primary defence against oxidative stress. The key function is to convert the reactive superoxide radicals into hydrogen peroxide and oxygen.

Because superoxide radicals are extremely harmful to cellular structures, their rapid removal is essential. Under mercury and salinity stress, SOD activity usually increases significantly as the plant attempts to control the initial burst of ROS production. By eliminating superoxide radicals, SOD prevents oxidative damage and reduces the likelihood of membrane and protein degradation.(Zeng et al., 2017)

7.1.2 Catalase (CAT)

SOD turns the superoxide radicals into H_2O_2, but if H_2O_2 is present at too high concentrations it can also become a toxic substance. This is resolved by the help of catalase that decomposes hydrogen peroxide to water and oxygen. Catalase is especially important as it effectively removes the high levels of H_2O_2 produced during stress. High levels of CAT activity are often measured when exposing plants to mercury or salinity stress. By removing H_2O_2 the efficiently, it provides protection to the membranes, chloroplasts and other cellular organelles against oxidation.(P. Sharma et al., 2007)

7.1.3 Peroxidase (POD)

Peroxidase is another major antioxidant enzyme playing a significant role in the breakdown of H_2O_2. POD uses variety of electron donors (phenolic compounds and ascorbate) rather than catalase in the conversion of H_2O_2 into H_2O.

Apart from the ROS scavenging activity, peroxidase is associated with cell strengthening and lignification process, thereby making plant capable to tolerate environmental stress. High activity of POD is associated with higher stress tolerance due to combined effect on antioxidant defines system and mechanical stability of the cell.

7.1.4 Glutathione-S-Transferase (GST)

The enzyme glutathione-S-transferase (GST) is also another crucial detoxification enzyme that plants use in response to environmental stress. While SOD, CAT and POD are more active against direct scavenging of ROS, the GST can provide an extra level of defines by acting to detoxify byproducts created under stress. In a situation like mercury toxicity and salinity stress excessive ROS may attack membrane lipids or other cellular structures and form a noxious by-product. GST attach this molecule with a very active reducing agent that is commonly found in plants, glutathione (GSH), which makes the molecule less noxious, therefore enabling the plant to transport it, store it or expel it. In mercury toxicity excessive oxidative damage and accumulation of toxic metabolites usually takes place in plant cells. GST can act in order to protect cellular components through the detoxification of mercury-generated oxidative products. In mercury toxicity, GST activity increases to enhance protection against the damage in cellular structures and maintain cellular homeostasis, and under salinity stress, it is active toward removal of the toxic compounds formed due to ionic imbalance and ROS generation. GSTs also have been shown to contribute to maintaining cellular redox balance and protection of proteins, membranes, and DNA from oxidative damage. Usually GST activity of the plant increases in response to stresses as plants employ to develop their adapted status and GST activity is thus accepted as a reliable parameter for evaluation of tolerance to stress.(Masoud et al., 2023)

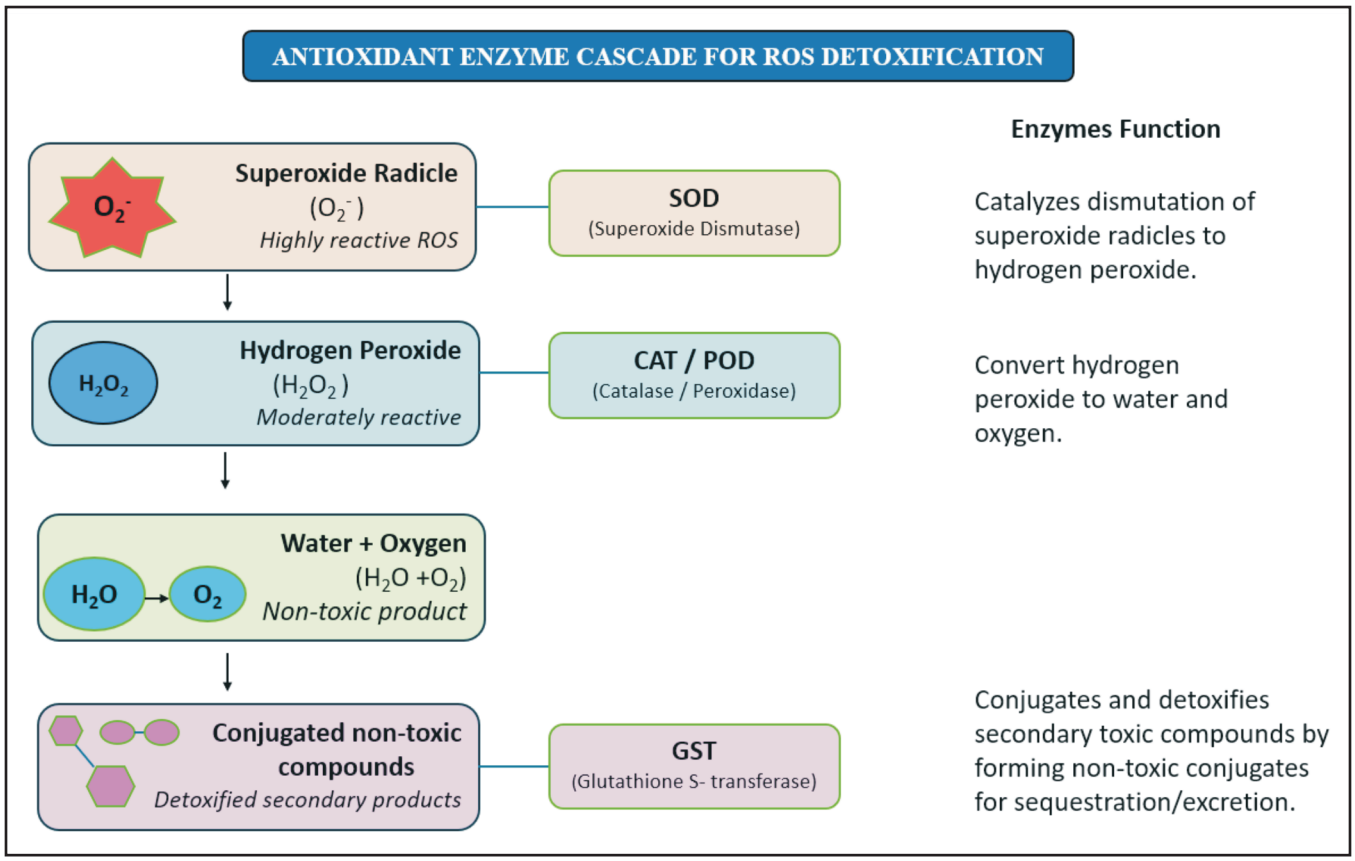


Figure 1: *Sequential breakdown of superoxide radicals into hydrogen peroxide by SOD ,followed by conversion into water and oxygen by CAT /POD ,and subsequent downstream detoxification by GST .*

8. Protective Role of Salicylic Acid

SA is a naturally occurring phenolic phytohormone which has a central role in helping plants cope with unfavourable environmental conditions. Over the years, SA has emerged as one of the most effective signalling molecules involved in plant stress tolerance. When plants encounter abiotic stresses such as heavy metal toxicity or salinity, their normal physiological and biochemical processes become disturbed, leading to reduced growth and excessive oxidative damage. Salicylic acid helps plants overcome these harmful effects by holding the stress- responsive pathways, activating antioxidant defence, maintaining homeostasis, and improving overall plant performance.(Gondor et al., 2016; Mahesh et al., 2017; Raskin, 1992; A. Sharma et al., 2020a)

In *Ocimum sanctum* (Tulsi), salicylic acid acts as a safeguarding agent that strengthens the plant□s natural defence system. It enhances growth, improves photosynthetic efficiency, regulates nutrient uptake, and reduces oxidative stress caused by environmental challenges. The beneficial effects of SA are particularly evident under mercury toxicity and salinity stress, where it helps plants maintain normal metabolic activities and survive under adverse conditions.(Khan et al., 2015; M. K. Sharma et al., 2002; Wani et al., 2017)

8.1 Protective Role of Salicylic Acid under Mercury Stress

One of the severest heavy metal toxicities that can be caused to plant growth is mercury (Hg). Following absorption by roots, mercury exerts several deleterious effects like interference in absorption of nutrient, injury to cell structure, suppression of photosynthesis, and excessive production of reactive species, resulting in inhibition of plant growth and yield.(Abbasi et al., 2023; Abdi et al., 2022; Gondor et al., 2016; Kalinhoff & Calderón, 2022; Khan et al., 2015; Raskin, 1992; Wani et al., 2017)

8.2 Effect of Salicylic Acid on the Growth of the Plant

One of the easily observable effects of salicylic acid application is its beneficial effects on the growth of plants under Hg stress. Mercury exposure results in the inhibition of root elongation, shoot growth, leaf expansion and biomass accumulation. The effect of salicylic acid counters the mercury mediated changes by sustaining cellular metabolic processes and normal growth development.(Abdi et al., 2022)

It enhances photosynthetic activities by two ways: one is protecting the damage of chlorophyll pigment and the other is to make the structure of chloroplast impairment. Under elevated photosynthetic rates the plant may produce sufficient energy and carbohydrate to make growth and repair. Besides, SA can enhance absorption of water and nutrients to assist physiological function to survive in Hg stress.(Chen et al., 2009)

As a result, SA-treated plants generally exhibit healthier roots, greener leaves, increased biomass and improved overall growth compared with untreated stressed plants.(Raskin, 1992)

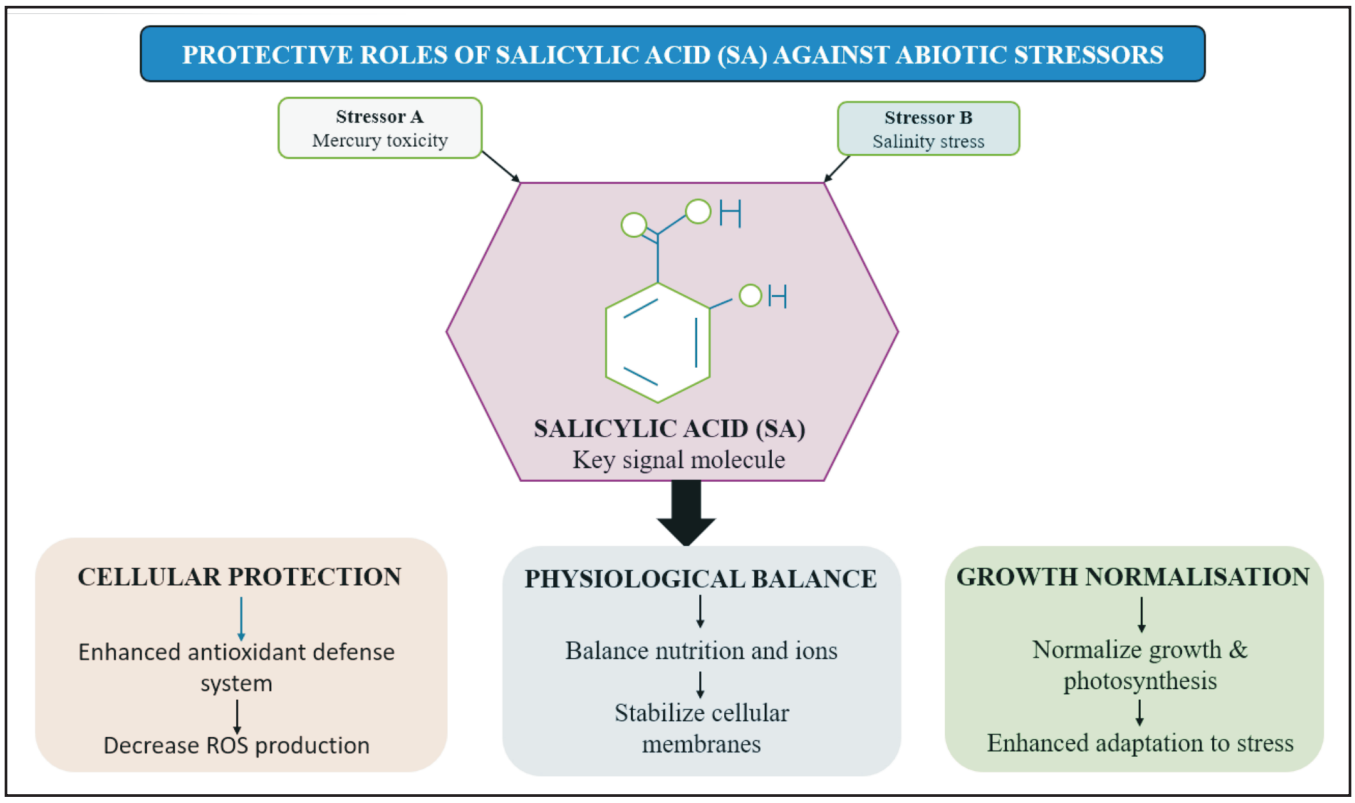


Figure 2: *Role of salicylic acid in reduction of ROS , membrane stabilization and ion balance to normalize photosynthesis and plant growth.*

8.4 Overall Significance of Salicylic Acid

Even though the toxicities caused by mercury and salinity stress are from different environmental stressors, SA regulates the stresses in similar protective mechanisms.SA helps to enhance antioxidant defence system, decrease ROS production, and stabilize cellular membrane, and photosynthetic process, also balances the nutrition and ions and normalizes growth. In this integrated way, SA is a major signal molecule regulating the adaptation to stress and protective agent for O. Sanctum against damage induced by the environmental stress.(Abbasi et al., 2023; Birben et al., 2012; Diringer et al., 2020; Qin et al., 2025; Tiodar et al., 2021)

9. Conclusion

Conditions of stress such as mercury and salinity are the constraint factors on growth of the plant and yield because they affect physiological and biochemical mechanisms of the plant by inducing stress due to oxidation. In *Ocimum sanctum*, mercury and salinity cause severe limitations on plant growth, photosynthesis and metabolic processes by causing over production of reactive oxygen species and by ionic perturbation. The mechanism of oxidative stress control involves an effective antioxidant system that plays a vital role to prevent cellular injury in plants under stress conditions. Enzymes, which form a part of the antioxidant system, are SOD, CAT and POD, while ascorbic acid, tocopherol etc. Constitutes non-enzymatic antioxidants of plants which help to maintain redox homeostasis of the plant tissues. Salicylic acid proves to be an efficient plant growth regulator which improve the plant to tolerate the stress condition in Tulsi by promoting defence mechanism, strengthening antioxidant enzymes, stabilize the membranes integrity and ionic content in salinity stress, and improving the heavy metal tolerance under metal stress conditions by enhancing the detoxification mechanism. The combination of all physiological, biochemical and molecular responses defines the tolerance capacity of *Ocimum sanctum* to survive stress conditions. These responses provide insight in plant stress biology and also potential ways to develop tolerant varieties.

10. Future Scope

Although our current knowledge of plant stress responses against mercury toxicity and salinity condition has gained a lot, there are some unexplored areas that needs further investigation: The precise molecular mechanisms underlying the stresses tolerance in *Ocimum sanctum* such as signalling pathway and gene networks involved in regulating the antioxidant activity need further studies. Studies on the use of salicylic acid in response to combined stresses are highly desired as so far; single stress condition has been studied. Exploring the combination of SA with other phytohormones or signalling molecules could give us more insights on integral stresses responses in plants.

We can also take the advantage of modern research approaches such as in the study of genome, protein and metabolism to identify key genes, proteins or metabolites involved in the stress outcomes against any stress factor in order to generate the biomarkers of stress resistance.

In a nutshell, research effort in the future must focus on translating laboratory knowledge to actual agricultural application so as to develop stress resistance and promote sustainable cultivation of medicinal plants such as *Ocimum sanctum*.

Conflict of Interest Statement

The authors declare no conflict of interest.

Ethical Declarations

The authors declare that this work does not involve human participants, animals, or any procedures requiring ethical approval.

References

- Abbasi, Q., Pourakbar, L., & Siavash Moghaddam, S. (2023). Potential role of apple wood biochar in mitigating mercury toxicity in corn (Zea mays L.). Ecotoxicology and Environmental Safety267, 115619. https://doi.org/10.1016/j.ecoenv.2023.115619
- Abdi, N., Van Biljon, A., Steyn, C., & Labuschagne, M. T. (2022). Salicylic Acid Improves Growth and Physiological Attributes and Salt Tolerance Differentially in Two Bread Wheat Cultivars. Plants11(14), 1853. https://doi.org/10.3390/plants11141853
- Agarwal, S., Kaushik, S., Saha, H., Paramanick, D., Mazhar, M., Basist, P., Khan, R., & Alhalmi, A. (2025). Therapeutic potential of traditional herbal plants and their polyphenols in alleviation of mercury toxicity. Naunyn-Schmiedeberg's Archives of Pharmacology398(7), 7737-7763. https://doi.org/10.1007/s00210-025-03807-7
- Akula, R., & Ravishankar, G. A. (2011). Influence of abiotic stress signals on secondary metabolites in plants. Plant Signaling & Behavior6(11), 1720-1731. https://doi.org/10.4161/psb.6.11.17613
- Alam, P., Balawi, T. A., & Faizan, M. (2022). Salicylic Acid's Impact on Growth, Photosynthesis, and Antioxidant Enzyme Activity of Triticum aestivum When Exposed to Salt. Molecules28(1), 100. https://doi.org/10.3390/molecules28010100
- An, C., & Mou, Z. (2011). Salicylic Acid and its Function in Plant ImmunityFJournal of Integrative Plant Biology, 53(6), 412-428. https://doi.org/10.1111/j.1744-7909.2011.01043.x
- Babu, K., & Uma Maheswari, K. C. (2006). In vivo studies on the effect of Ocimum sanctum L. leaf extract in modifying the genotoxicity induced by chromium and mercury in Allium root meristems. Journal of Environmental Biology27(1), 93-95.
- Birben, E., Sahiner, U. M., Sackesen, C., Erzurum, S., & Kalayci, O. (2012). Oxidative Stress and Antioxidant Defense. World Allergy Organization Journal5(1), 9-19. https://doi.org/10.1097/WOX.0b013e3182439613
- Chen, Z., Zheng, Z., Huang, J., Lai, Z., & Fan, B. (2009). Biosynthesis of salicylic acid in plants. Plant Signaling & Behavior4(6), 493-496. https://doi.org/10.4161/psb.4.6.8392

- Cohen, M. M. (2014). Tulsi - Ocimum sanctum: A herb for all reasons. Journal of Ayurveda and Integrative Medicine5(4), 251-259. https://doi.org/10.4103/0975-9476.146554
- De Los Reyes, B. G., Myers, S. J., & McGrath, J. M. (2003). Differential induction of glyoxylate cycle enzymes by stress as a marker for seedling vigor in sugar beet (Beta vulgaris). Molecular Genetics and Genomics269(5), 692-698. https://doi.org/10.1007/s00438-003-0875-6
- Diringer, S. E., Berky, A. J., Marani, M., Ortiz, E. J., Karatum, O., Plata, D. L., Pan, W. K., & Hsu-Kim, H. (2020). Deforestation Due to Artisanal and Small-Scale Gold Mining Exacerbates Soil and Mercury Mobilization in Madre de Dios, Peru. Environmental Science & Technology54(1), 286□296. https://doi.org/10.1021/acs.est.9b06620
- Emamverdian, A., Ding, Y., & Mokhberdoran, F. (2020). The role of salicylic acid and gibberellin signaling in plant responses to abiotic stress with an emphasis on heavy metals. Plant Signaling & Behavior15(7), 1777372. https://doi.org/10.1080/15592324.2020.1777372
- Genc, Y., Taylor, J., Lyons, G., Li, Y., Cheong, J., Appelbee, M., Oldach, K., & Sutton, T. (2019). Bread Wheat With High Salinity and Sodicity Tolerance. Frontiers in Plant Science10, 1280. https://doi.org/10.3389/fpls.2019.01280
- Gondor, O. K., Pál, M., Darkó, É., Janda, T., & Szalai, G. (2016). Salicylic Acid and Sodium Salicylate Alleviate Cadmium Toxicity to Different Extents in Maize (Zea mays L.). PLOS ONE11(8), e0160157. https://doi.org/10.1371/journal.pone.0160157
- Gupta, S., & Seth, C. S. (2021). Salicylic acid alleviates chromium (VI) toxicity by restricting its uptake, improving photosynthesis and augmenting antioxidant defense in Solanum lycopersicum L. Physiology and Molecular Biology of Plants27(11), 2651□2664. https://doi.org/10.1007/s12298-021-01088-x
- Hussain, M., Farooq, S., Hasan, W., Ul-Allah, S., Tanveer, M., Farooq, M., & Nawaz, A. (2018). Drought stress in sunflower: Physiological effects and its management through breeding and agronomic alternatives. Agricultural Water Management201, 152□166. https://doi.org/10.1016/j.agwat.2018.01.028
- Ýþkil, R., Surgun-Acar, Y., Çatav, Þ. S., Zemheri-Navruz, F., & Erden, Y. (2022). Mercury toxicity affects oxidative metabolism and induces stress responsive mechanisms in wheat (Triticum aestivum L.). Physiology and Molecular Biology of Plants28(4), 911-920. https://doi.org/10.1007/s12298-022-01171-x
- Issac Abraham, S. V. P., Arumugam, V. R., Mary, N. I., Dharmadhas, J. S., Sundararaj, R., Devanesan, A. A., Rajamanickam, R., Veerapandian, R., John Bosco, J. P., & Danaraj, J. (2024). Ocimum sanctum as a Source of Quorum Sensing Inhibitors to Combat Antibiotic Resistance of Human and Aquaculture Pathogens. Life14(7), 785. https://doi.org/10.3390/life14070785
- Kalinhoff, C., & Calderón, N.-T. (2022). Mercury Phytotoxicity and Tolerance in Three Wild Plants during Germination and Seedling Development. Plants11(15), 2046. https://doi.org/10.3390/plants11152046
- Khalid, M. F., Elezz, A. A., Jawaid, M. Z., & Ahmed, T. (2023). Salicylic acid restricts mercury translocation by activating strong antioxidant defense mechanisms in sweet pepper (Capsicum annum L.). Environmental Technology & Innovation32, 103283. https://doi.org/10.1016/j.eti.2023.103283
- Khan, M. I. R., Fatma, M., Per, T. S., Anjum, N. A., & Khan, N. A. (2015). Salicylic acid-induced abiotic stress tolerance and underlying mechanisms in plants. Frontiers in Plant Science6. https://doi.org/10.3389/fpls.2015.00462
- Ko, C.-B., Woo, Y.-M., Lee, D. J., Lee, M.-C., & Kim, C. S. (2007). Enhanced tolerance to heat stress in transgenic plants expressing the GASA4 gene. Plant Physiology and Biochemistry45(9), 722□728. https://doi.org/10.1016/j.plaphy.2007.07.010
- Li, A., Sun, X., & Liu, L. (2022). Action of Salicylic Acid on Plant Growth. Frontiers in Plant Science13, 878076. https://doi.org/10.3389/fpls.2022.878076
- MacDonald, M. T., & Mohan, V. R. (2025). Chemical Seed Priming: Molecules and Mechanisms for Enhancing Plant Germination, Growth, and Stress Tolerance. Current Issues in Molecular Biology47(3), 177. https://doi.org/10.3390/cimb47030177
- Mahesh, H. M., Murali, M., Anup Chandra Pal, M., Melvin, P., & Sharada, M. S. (2017). Salicylic acid seed priming instigates defense mechanism by inducing PR-Proteins in Solanum melongena L. upon infection with Verticillium dahliae Kleb. Plant Physiology and Biochemistry: PPB117, 12□23. https://doi.org/10.1016/j.plaphy.2017.05.012
- Mahgoub, S. M., Alawam, A. S., Allam, A. A., M. M., M. M., Mokhtar, A. M., Radalla, A. M., & Mahmoud, R. (2025). Development of a salicylic acid-encapsulated zeolite□seaweed biochar composite for sustainable agricultural applications. RSC Advances15(54), 46570□46590. https://doi.org/10.1039/D5RA06953J
- Maruri-López, I., Aviles-Baltazar, N. Y., Buchala, A., & Serrano, M. (2019). Intra and Extracellular Journey of the Phytohormone Salicylic Acid. Frontiers in Plant Science10, 423. https://doi.org/10.3389/fpls.2019.00423
- Masoud, H. M. M., Helmy, M. S., Darwish, D. A., & Ibrahim, M. A. (2023). Purification, characterization, and enzyme kinetics of a glutathione S transferase from larvae of the camel tick Hyalomma dromedarii. Journal of Genetic Engineering and Biotechnology21(1), 28. https://doi.org/10.1186/s43141-023-00486-w
- Misra, N., & Saxena, P. (2009). Effect of salicylic acid on proline metabolism in lentil grown under salinity stress. Plant Science177(3), 181-189. https://doi.org/10.1016/j.plantsci.2009.05.007
- Murugan, S. K., Bethapudi, B., Mundkinajeddu, D., & D□Souza, P. (2025). Assessment of genotoxicity and acute oral toxicity of a standardized Ocimum tenuiflorumTM). Drug and Chemical Toxicology, 48(3), 530-539. https://doi.org/10.1080/01480545.2024.2429619
- Nowicki, M., Nowakowska, M., Nowak, K., Szczechura, W., & Kaminski, P. (2025). Seed priming and abiotic stress tolerance in carrot: Unraveling the mechanisms of improved germination. PLOS ONE20(2), e0318753. https://doi.org/10.1371/journal.pone.0318753

- Qin, C., Zhang, Z., Xi, W., Shi, C., Lei, H., He, Z., Begum, N., & Lian, H. (2025). Gibberellic acid and spermine induce mercury tolerance in tomato seedlings by modulating osmolyte, redox homeostasis and detoxification system. BMC Plant Biology25(1), 1140. https://doi.org/10.1186/s12870-025-06674-9
- Rafati-Rahimzadeh, M., Rafati-Rahimzadeh, M., Kazemi, S., & Moghadamnia, A. A. (2014). Current approaches of the management of mercury poisoning: Need of the hour. DARU Journal of Pharmaceutical Sciences22(1), 46. https://doi.org/10.1186/2008-2231-22-46
- Raskin, I. (1992). Role of Salicylic Acid in Plants. Annual Review of Plant Physiology and Plant Molecular Biology43(1), 439□463. https://doi.org/10.1146/annurev.pp.43.060192.002255
- Rithichai, P., Jirakiattikul, Y., Nambuddee, R., & Itharat, A. (2024). Effect of Salicylic Acid Foliar Application on Bioactive Compounds and Antioxidant Activity in Holy Basil (Ocimum sanctum L.). International Journal of Agronomy2024, 1-8. https://doi.org/10.1155/2024/8159886
- Sahoo, R. K., & Tuteja, N. (2013). Effect of salinity tolerant PDH45 transgenic rice on physicochemical properties, enzymatic activities and microbial communities of rhizosphere soils. Plant Signaling & Behavior8(8), e24950. https://doi.org/10.4161/psb.24950
- Sharma, A., Sidhu, G. P. S., Araniti, F., Bali, A. S., Shahzad, B., Tripathi, D. K., Brestic, M., Skalicky, M., & Landi, M. (2020a). The Role of Salicylic Acid in Plants Exposed to Heavy Metals. Molecules25(3), 540. https://doi.org/10.3390/molecules25030540
- Sharma, A., Sidhu, G. P. S., Araniti, F., Bali, A. S., Shahzad, B., Tripathi, D. K., Brestic, M., Skalicky, M., & Landi, M. (2020b). The Role of Salicylic Acid in Plants Exposed to Heavy Metals. Molecules25(3), 540. https://doi.org/10.3390/molecules25030540
- Sharma, M. K., Kumar, M., & Kumar, A. (2002). Ocimum sanctum aqueous leaf extract provides protection against mercury induced toxicity in Swiss albino mice. Indian Journal of Experimental Biology40(9), 1079-1082.
- Sharma, P., Bhardwaj, R., Arora, N., & Arora, H. K. (2007). Effect of 28-homobrassinolide on growth, zinc metal uptake and antioxidative enzyme activities in Brassica juncea L. seedlings. Brazilian Journal of Plant Physiology19(3), 203-210. https://doi.org/10.1590/S1677-04202007000300004
- Tiodar, E. D., Vãcar, C. L., & Podar, D. (2021). Phytoremediation and Microorganisms-Assisted Phytoremediation of Mercury-Contaminated Soils: Challenges and Perspectives. International Journal of Environmental Research and Public Health18(5), 2435. https://doi.org/10.3390/ijerph18052435
- Unsal, V. (2018). Natural Phytotherapeutic Antioxidants in the Treatment of Mercury Intoxication-A Review. Advanced Pharmaceutical Bulletin8(3), 365□376. https://doi.org/10.15171/apb.2018.043
- Wahab, A., Abdi, G., Saleem, M. H., Ali, B., Ullah, S., Shah, W., Mumtaz, S., Yasin, G., Muresan, C. C., & Marc, R. A. (2022). Plants□ Physio-Biochemical and Phyto-Hormonal Responses to Alleviate the Adverse Effects of Drought Stress: A Comprehensive Review. Plants11(13), 1620. https://doi.org/10.3390/plants11131620
- Wang, H., Li, Y., Wassie, M., Huo, L., & Shi, H. (2024). Salicylic Acid Spray Delays Sand Pear Fruit Senescence during Room Temperature Shelf Life by Regulating Antioxidant Capacity and Senescence-Related Genes. Plants13(6), 848. https://doi.org/10.3390/plants13060848
- Wani, A. B., Chadar, H., Wani, A. H., Singh, S., & Upadhyay, N. (2017). Salicylic acid to decrease plant stress. Environmental Chemistry Letters15(1), 101-123. https://doi.org/10.1007/s10311-016-0584-0
- Zeng, J., Sheng, H., Liu, Y., Wang, Y., Wang, Y., Kang, H., Fan, X., Sha, L., Yuan, S., & Zhou, Y. (2017). High Nitrogen Supply Induces Physiological Responsiveness to Long Photoperiod in Barley. Frontiers in Plant Science8, 569. https://doi.org/10.3389/fpls.2017.00569

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