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Review Article

Vanadium Stress Mitigants in Plants: From Laboratory to Field Implications

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ABSTRACT

Horticultural crops irrigated with sewage wastewater have enhanced metal toxicity. Among heavy metals, vanadium most adversely affects vegetative growth, crop yield, and overall fruit quality of horticultural crops globally. The accumulation of vanadium metal disrupts different physiological processes of plants, influencing the overall performance, including growth, yield and quality aspects. Horticultural crops subjected to vanadium toxicity exhibit reduced photosynthesis, metabolic disturbances, and imbalanced nutrient assimilation. Metabolic processes are impaired due to oxidative harms under vanadium toxicity. However, the activation of enzymatic properties was also revealed under vanadium toxicity to cope with oxidative harm. So, different management practices can be used to lessen the adverse effects of vanadium toxicity. These management approaches include the utilization of phytohormones, bio-stimulants, soil microorganisms, biochar, and the selection of vanadium-tolerant cultivars. The application of these management strategies has the potential to lessen vanadium toxicity in horticultural crops. So, the present review explores applying different mitigation strategies to improve stress tolerance against vanadium toxicity in horticulture crops.

Keywords: *Cultivation of tolerant germplasm, low-quality produce, metabolism disruption, toxic substances.*

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INTRODUCTION

Vanadium is the sixth most abundant transition metal on earth. It is widely found in the soils of China, Russia, the United States, and South Africa (Amorim et al., 2007; Gan et al., 2021). China is the largest producer and user of the metal globally (Tripathi et al., 2018). Many organic and inorganic processes, such as the ageing of rock sources, redox reactions, leaching, the use of fertilizers, burning, and industrial byproducts, are the main sources for the widespread distribution and mobilization of vanadium. Therefore, vanadium pollutes the water, soil, and environment (Tian et al., 2015). Vanadium is found in soil ranging from 3-310 mg kg^{-1}. Vanadium content in fresh, ground, and drinking water ranges from 0.5 μg L^{-1} on a median, peaking at 127.4 μg L^{-1} in volcanic regions (Wu et al., 2021). Vanadium builds up in natural habitats, contaminating water as well as soil and eventually harming human health through nausea, vomiting, vertigo, and, more dangerously, kidney impairment (He et al., 2020). Several researchers have explored the negative effects of vanadium toxicity on plant growth and yield due to induced oxidative stress (Larsson et al., 2013; Wu et al., 2021).

The oxidation phase of vanadium affects its accessibility, bioaccumulation, and cytotoxicity. The poisonous substance vanadate, which is derived from vanadium, inhibits the biological, biochemical, and morphological processes of plants in elevated amounts, ultimately impeding plant growth and yield (García-Jiménez et al., 2018; Wu et al., 2021). Plants may readily absorb vanadium through the soil; nevertheless, the amount of vanadium in the soil affects the plants. Plant growth, transpiration, and gas exchange factors are improved by low levels of vanadium supplementation (Chen et al., 2016). An increase in the production of reactive oxygen species (ROS), cell membranes rupturing, antioxidant enzymes activation, metabolism disturbances, and transcription of genes are all consequences of excessive vanadium intervention on plant health (Sridhara Chary et al., 2008; Reiter et al., 2015). By producing more osmolytes and polyphenols and boosting the functioning of antioxidant enzymes, plants can withstand oxidative harm and neutralize ROS (Kumar et al., 2021). Previous research demonstrated the impact of vanadium on plant physiology by modifying or lowering the rate of photosynthetic respiration, root and shoot survival, and chlorosis in the leaves (Reiter et al., 2015; Kumar et al., 2021).

Photosynthesis is an essential metabolic mechanism in plants that boosts yields and absorption of carbon. Exposure to heavy metal can significantly impair both its generation and

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Table 1: The adverse effects of vanadium on growth, yield and quality of horticultural crops.

Crop names	Stress levels	Adverse effects	References
Watermelon	50 mg L^{-1}	Stunted root and shoot growth. Poor photosynthetic assimilation. Low chlorophyll content formation. Over-generation of toxic ROS in cells.	Nawaz et al. (2018)
Peppers	0, 10, 20, 30, 40, and 50 mg L^{-1}	Root growth and photosynthetic pigments of pepper seedlings were disturbed due to elevated vanadium levels. Lipid peroxidation and membrane injury increased.	Altaf et al. (2021)
Sweet potato	0, 10, 25, 50, and 75 mg L^{-1}	10 mg L^{-1} improved plant biomass, while other concentrations drastically reduced the biomass. ROS generation is enhanced due to vanadium toxicity.	Kumar et al. (2022)
Tomato	40 mg L^{-1}	Tomato seedlings showed distress in mineral uptake, photosynthesis, root characteristics, and antioxidant apparatus. Membrane injury enhanced.	Altaf et al. (2022a)
Pepper and tomato	0, 3, 5, and 10 mg L^{-1}	Poor growth of seedlings. Low phenolic content synthesis if leaves. Disturbances in photosynthesis.	Saldaña-Sánchez et al. (2019)
Peppers	0, 5, 10, and 15 µM	Applying 5 µM vanadium increased plant growth, induced floral bud development, and accelerated flowering. With 10 and 15 µM vanadium, the plants were smaller and showed toxicity symptoms.	García-Jiménez et al. (2018)
Tomato	0, 5, 10, and 15 µM	5 and 10 µM vanadium stimulates a number of leaves and flowering traits in tomatoes. 15 µM vanadium showed toxicity symptoms. 15 µM vanadium decreased the fresh and dry biomass of tomatoes.	Garcia-Jimenez et al. (2021)
Red cabbage	0, 2.0, 4.0, and 6.0 mg L^{-1}	The induced vanadium leads to an increase in the bioaccumulation of vanadium in plant tissues and the seriousness of toxicity due to the overproduction of ROS, which leads to oxidative stress.	Doklega et al. (2022)
Watermelon	40 mg L^{-1}	Stunted growth of watermelon. ROS overproduction. Membrane rupturing. Metabolism disturbances.	Shireen et al. (2021)
Moring glory	0–2.5 mg L^{-1}	Low root growth and poor photosynthetic pigments due to vanadium levels. Plant biomass was stimulated at low levels of vanadium less than 0.1 mg L^{-1}.	Chen et al. (2016)

assimilation (Altaf et al., 2021). Under heavy metal stress, especially vanadium toxicity, several studies have shown an extensive decrease in photosynthesis and gas exchange components in pepper and watermelon (Nawaz et al., 2018). Blocking electron transport and weakening the chloroplast's membrane resilience can harm photosynthetic pigments. Similarly, plant roots become the vital organ responsible for interacting with and absorbing soil metal (León-Morales et al., 2019). The primary defence against toxic heavy metals is a plant's roots, which provide structural stability. Plant tolerance can be improved by reducing the absorption of superfluous metal (Aihemaiti et al., 2020). Previous research also showed that certain plants' root structure was dramatically diminished at greater levels of vanadium treatment (García-Jiménez et al., 2018). However, optimal concentrations of vanadium metal and their impacts on horticultural crops can be further explored for sustainable farming (Table 1).

Sustainable cultivation of horticulture crops is economically important within the country. Vanadium toxicity is reported in several horticultural and field crops, such as peppers (García-Jiménez et al., 2018), alfalfa (Gan et al., 2020), and rice (Yuan et al., 2020). Different management approaches such as bio-stimulant application, use of phytohormones and plant growth regulators, application of different minerals, utilization of biochar, soil microbes and uptake of minerals, and grafting approaches can mitigate the adverse effects of vanadium toxicity (Table 2). The present review encourages the beneficial role of bio-stimulant application, utilization of biochar, soil microbes, minerals assimilation, and grafting approaches that can effectively alleviate vanadium toxicity in horticulture crops.

EFFECTS OF VANADIUM STRESS ON PLANT GROWTH, YIELD AND QUALITY

Vegetative and reproductive growth

Excessive vanadium inhibits plant growth, alters physiological and biochemical activities, and enhances the production of ROS (Kumar et al., 2022). Numerous studies have reported that the toxicity of plants induced by vanadium includes reducing plant biomass, altering enzymatic activities, decreasing nutrient absorption, inhibiting chlorophyll and protein production, impairing cell wall formation, and even causing cell apoptosis

(Aihemaiti et al., 2020; Roychoudhury, 2020). ROS overproduction in plants may enhance the negative effects of oxidative stress including chromosomal damage, metabolic disruption, increased cell membrane permeability, enzyme inhibition, and promotion of cell-damaging lipid peroxidation (Tripathi et al., 2018; Chen et al., 2021).

Vanadium toxicity has pronounced effects on the root architecture and morphology of plants, which can have significant implications for their overall growth and development (Tripathi et al., 2018). An exposure to the elevated levels of vanadium can disrupt root growth and alter the root architecture. Moreover, vanadium toxicity also results in a reduction of primary root length and lateral root development (Altaf et al., 2022a). The inhibition of root elongation and branching results in a decreased surface area for nutrient and water absorption, impairing the plant's ability to uptake essential resources from the soil (Vachirapatama et al., 2011). Vanadium toxicity can also affect root morphology, changing things like root diameter and root hair development, as reported in *Arabidopsis thaliana* (Rojek et al., 2019). These modifications may also affect the effectiveness of nutrient uptake and interactions between roots and soil (Altaf et al., 2022b). It is crucial to comprehend the effects of vanadium toxicity on root architecture and morphology for adopting strategies to lessen the harmful impacts of vanadium toxicity on plant growth and increase the resilience of horticulture crops in vanadium-contaminated environments.

The elevated levels of vanadium can interfere with physiological and hormonal processes, delaying flowering and fruiting (Vachirapatama et al., 2011). Furthermore, vanadium-induced oxidative stress can also affect the development of reproductive structures, preventing flower bud formation and impairing pollen viability. This can reduce pollination and fertilization rates, resulting in a decrease in fruit yield (Altaf et al., 2021; Wu et al., 2022). Vanadium poisoning can also disrupt the manufacture and communication of plant hormones like auxins and gibberellins, which are essential for the growth of flowers and fruits (Altaf et al., 2022a).

Yield and produce quality

Vanadium toxicity has several negative impacts on fruit quality and yield and affects the growth and development of horticultural crops. Moreover, fruit size, weight, and yield may decrease because of high vanadium levels (Vachirapatama et al., 2011). The fruit's biochemical quality may be adversely impacted by vanadium, changing its flavour, aroma, and nutritional value (Altaf et al., 2021). Important constituents, including sugars, organic acids, and antioxidants, may diminish as a result, lowering the quality of the produce, as reported in lettuce by Wu et al. (2022). Vanadium poisoning can disturb the plant's hormonal balance, leading to early fruit drop. Furthermore, vanadium stress's disruption of nutrient intake can lead to nutritional deficits, further reducing fruit quality and output (Doklega et al., 2022). Therefore, it is crucial to reduce vanadium toxicity in horticultural crops to maintain fruit quality, assure optimal fruit production, and satisfy consumer needs for fruit that is marketable, tasty, and nutritious. Vanadium-stressed plants may have irregular or delayed flower opening, delayed fruit development, and inferior fruit quality (Shireen et al., 2021). Understanding how vanadium toxicity affects fruiting and flowering is crucial for developing effective mitigation techniques that will lessen these effects and guarantee optimum reproductive health and crop output.

TOLERANCE MECHANISM IN RESPONSE TO VANADIUM TOXICITY

The alteration in hormonal levels, disruption in photosynthesis, accumulation of ROS, and poor nutrient uptake and assimilation are some consequences in horticulture crops because of vanadium toxicity (Gokul et al., 2018). These influences can greatly impact the growth, development, and general production of horticulture crops (Altaf et al., 2021). The impairment of photosynthesis, the vital mechanism through which plants transform light energy into chemical energy, is one of the main effects of vanadium toxicity (Buendía-Valverde et al., 2023). Metal toxicity can interfere with photosynthesis by modifying the amount of chlorophyll, suppressing enzyme activity, and changing photosystem work (Pardo-Hernández et al., 2021). Moreover, reduced photosynthetic rate, lower light absorption efficiency, and poorer carbon uptake result from the metals' toxicity. Lower crop yields and reduced biomass output result from vanadium toxicity (Xie et al., 2022).

The buildup of ROS within plant cells is another effect of vanadium toxicity. Through redox processes, vanadium ions can produce ROS, including superoxide radicals, hydrogen peroxide, and hydroxyl radicals (Altaf et al., 2022b). Oxidative stress is induced by an overabundance of ROS, which overwhelms the plant's antioxidant defence mechanism (Farooq et al., 2019). ROS buildup causes oxidative damage to lipids, proteins, and DNA, among other biological constituents (Racchi, 2013). Therefore, plant growth and development are hampered when cellular architecture and functions are disturbed. Vanadium toxicity can also interfere with the uptake and assimilation of nutrients used in horticultural crops. It can compete with other necessary nutrients for absorption and binding sites in the plant, like iron, calcium, and magnesium (Aihemaiti et al., 2020). So, numerous metabolic processes may be impaired by nutritional imbalances and inadequacies due to the competition. Vanadium can also hinder the movement and absorption of nutrients inside plants, impacting their overall nutrient status (Aihemaiti et al., 2020). The breakdown of nutritional homeostasis further jeopardises crop quality, nutrient uptake, and plant growth (Tripathi et al., 2018). Vanadium toxicity can also change the hormonal composition of horticultural crops. Hormones are essential for controlling several physiological processes, including growth, development, and stress reactions (Chen et al., 2021). Vanadium can interfere with the signalling, metabolism, and production of hormones. It can obstruct the transport and perception of plant hormones such as auxins, cytokinins, gibberellins, and abscisic acid as well as their synthesis (Chen et al., 2016). The cell division, elongation, flowering, fruiting, and other developmental processes may be impacted by these changes in hormone levels and signalling pathways in horticultural crops (Vachirapatama et al., 2011).

Developing mitigation measures requires a thorough understanding of the impact of vanadium toxicity on reduced photosynthesis, the buildup of ROS, disturbance of nutrient absorption and assimilation, and changed hormone levels (Nawaz et al., 2018). Implementing vanadium reduction options, such as soil remediation methods, can help mitigate the detrimental effects on crop development and yield (Gangwar et al., 2014; Khan et al., 2022). Applying exogenous chemicals such as antioxidants, Osmo protectants, and plant growth regulators may lessen the consequences of vanadium-induced stress by enhancing stress tolerance and reducing oxidative damage (Nawaz et al., 2018). It is also possible to investigate genetic methods like genetic engineering to create crop kinds that can withstand vanadium. Horticultural crops can be safeguarded from the negative impacts of vanadium toxicity by addressing these consequences and putting in place suitable mitigation techniques, assuring sustainable and effective agricultural practices (Hoque et al., 2021; Khan et al., 2022; Xie et al., 2022).

MANAGEMENT APPROACHES TO ALLEVIATE THE VANADIUM STRESS IN HORTICULTURAL CROPS

Biochar application for alleviation of vanadium stress

Globally, the rate of urbanization and industrialization has accelerated, leading to an upsurge in pollution caused by heavy metals (Lou et al., 2016). In addition to being a major health risk to people and animals, pollution from heavy metals exerts a detrimental impact on crop quality, production, as well as soil condition (Feng et al., 2023). Carbon rice, or biochar, is made through the oxygen-free pyrolysis of various raw materials (Lou et al., 2016). Because of its distinct physio-chemical properties, it has drawn a lot of attention from around the world as an eco-friendly, cutting-edge, and durable tool for agriculture, energy generation, and environmental protection (Velli et al., 2021). Biochar is a valuable addition for utilization in agriculture because of its high particular area, surface action, improved structure with pores, oxygen-rich functional groups, and increased ion exchange potential (Awad et al., 2022). In the last few years, biochar has gained popularity as a crucial instrument for controlling pollution in the environment and cleaning up polluted soils (Almaroai and Eissa, 2020). It also has the added advantages of enhancing fertility in soils, improving soil quality, and storing carbon (Sarma et al., 2019). Toxic metals decreased antioxidant activity, resulting, in turn, a notable decline in plant growth. So, by inactivating the hazardous metals, the use of biochar reduced their biological activity (Wang et al., 2023a). Another investigation found that applying biochar enhanced the proliferation of metal-tolerant, imparting gene and antioxidant genes, improving resistance to vanadium (Dai et al., 2018).

The two primary fundamental parts of biochar, which is a robust carbon molecule, are randomly organized amorphous aromatic molecules as well as paired crystalline graphene sheets. Biochar is produced via pyrolysis, a heat process that breaks down organic molecules (Ahmed et al., 2021). The amount of aromatic carbon in the biochar increases as the temperature rises throughout pyrolysis. Moreover, biochar also helps to retain water as well as nutrients, stops dangerous bacteria from growing, removes heavy metals as well as pesticides, stops soil loss, raises the soil pH, enhances cationic transaction, and promotes soil fertility (Sarma et al., 2019). Polluting substances in soils can be retained by biochar. To combat the harmful effects of ROS on crops, biochar dramatically alters the ROS cleaning enzymes and, therefore, offers an effective electron-transferring channel (Dai et al., 2018). Although rice husk biochar, as well as wood biochar that had fewer functional groups, showed higher surface regions and porosity, they were less successful in immobilizing vanadium and lowering its plant absorption (Shakya and Agarwal., 2020; Haider et al., 2022).

The wood biochar with rich O-containing structural sites was more successful in both processes. Furthermore, it was shown that several parameters primarily regulated the dissolution as well as transpiration of vanadium in soil enriched in biochar (Natasha et al., 2022). Improvements in soil acidity with soluble aromatic organic carbon potentially immobilize vanadium and reduce its toxicological risk, whereas rises in soil pH, as well as soluble hydrocarbon, may promote vanadium mobilization and phytoremediation (Subedi et al., 2017). So, by enhancing antioxidant activity and lowering ROS generation, applying biochar to mustard plants promotes growth and biomass output reported by a few other plant researchers (Subedi et al., 2017; Khan et al., 2022).

Table 2: The use of various stress mitigants and their potential effects on horticultural crops against vanadium toxicity.

Stress mitigants name	Use of stress mitigants	Crop names	Impacts	References
Boron	75 µM	Watermelon	Boron reduced the toxic effects of vanadium by improving plant growth and antioxidant defense system Boron promoted chelation of vanadium in cell wall and sequestration in vacuole.	Shireen et al. (2021)
Melatonin	100 µM	Tomato	Boosting photosynthesis, biomass production, redox balance, nutrient uptake, and root traits	Altaf et al. (2022a)
Grafting	Watermelon was grafted onto bottle gourd and pumpkin	Watermelon, Bottle gourd, and pumpkin	Vanadium tolerance improved in watermelon by reducing the vanadium concentration in leaf tissues, improving the SPAD index, and photosynthesis, and upregulating the defense system.	Nawaz et al. (2018)
Plant growth promoting rhizobacteria	*Serratia marcescens PRE01*	*Pteris vittate* (Fern species)	Inoculation with endophytes is a promising method for modulating multiple strategies to enhance the phytoremediation of vanadium-contaminated soils.	Wang et al. (2023b)

Potential effect of grafting against vanadium stress in vegetables

The process of grafting, which involves uniting scion and rootstock from the same or different plant species to form a new plant, is a significant horticultural technique (Goldschmidt, 2014). The practical use of this method has been widely tested against various kinds of stresses in horticultural crops (Nawaz et al., 2016; Drobek et al., 2019). By excluding or retaining/accumulating heavy metals in the roots, grafting can reduce heavy metal stress in a variety of crops (Güçlü et al., 2003). The vanadium concentration of 50 µM significantly inhibits the growth of watermelon. Watermelon's resistance to vanadium damage and plant growth is enhanced by the incorporation of bottle gourd as well as pumpkin rootstock (Nawaz et al., 2018). Through grafting watermelon over the above rootstocks, the corresponding chlorophyll content, as well as photosynthetic integration, are improved (Ceylan et al., 2018). The vanadium level within the leaf tissue is decreased, antioxidant-related genomes are up-regulated, enzymatic activities are improved, and oxidative injury level is decreased, and protecting the leaves (Edelstein et al., 2017). While it has been documented that several heavy metals, including Cu, Cr, Ni, Cd, Sr, and Ti, can be better tolerated by using rootstocks, there is currently no additional information on the possibility of grafting to increase vegetable resistance to metals toxicity (Savvas et al., 2010). Research is needed to fully comprehend the discriminatory procedure of pumpkin rootstock in the distribution of vanadium and P, as P levels in the leaf tissue of self-grafted along with bottle gourd-grafted watermelon crops decreased in vanadium toxicity circumstances, but did not change in the context of pumpkin grafted watermelon (Nawaz et al., 2018).

Application of phytohormones against vanadium stress in plants

Vanadium poisoning of fertile soils has been a danger to world crop supplies in the last few years. Plants naturally produce substances called phytohormones, which are crucial for controlling the growth and maturation of plants (Nguyen et al., 2021). Plants can recognize metal toxicity and initiate a variety of signalling cascades. Plant hormones, which are either exogenous or natural, help to lessen the stress that vanadium causes in tomato seedlings (Altaf et al., 2022a). Moreover, determining the role of phytohormones in plants during vanadium toxicity has advanced significantly in the past decade. Horticultural plants' ability to withstand metal toxicity can be improved by phytohormones (Popova et al., 2012). Vanadium is a hazardous heavy metal that can build up in plant tissues and result in some physicochemical alterations that impede growth and production (Kumar et al., 2022). It has been demonstrated that phytohormones are crucial for controlling plant growth and development as well as how plants react to different heavy metal stressors (Emamverdian et al., 2020; Sharma et al., 2020). A few investigations have shown that external phytohormone treatment can enhance plant development and lessen metals harmful effects on horticulture plants (Sharma et al., 2020; Khalil et al., 2021). Melatonin promotes root development and lessens vanadium buildup in plant tissues, while melatonin also increases antioxidant activity and lessens vanadium-induced oxidative damage (Nawaz et al., 2018). Therefore, increasing plant development and output in soil contaminated with vanadium may be possible with the application of phytohormones to increase plants' resistance to vanadium distress. Melatonin is a well-researched biomolecule that functions as an antioxidant in stressful environments, one of the many drugs that relieve stress (Yang et al., 2023). According to earlier findings, vanadium (40 mg L^{-1}) stress resulted in the reduction of productivity due to deficiencies in photosynthetic networks, root characteristics, and balance of minerals. On the other hand, melatonin (100 µM) treatment resulted in a significant reinforcement of plant growth parameters, including diminished vanadium buildup and enhanced mineral nutrient stability, gas exchange variables, root shape, and levels of chlorophyll (Altaf et al., 2022a). The use of melatonin increases plant growth, reduces the amount of vanadium available in the plant, and enhances a plant's capacity to withstand vanadium distress (Moustafa-Farag et al., 2020).

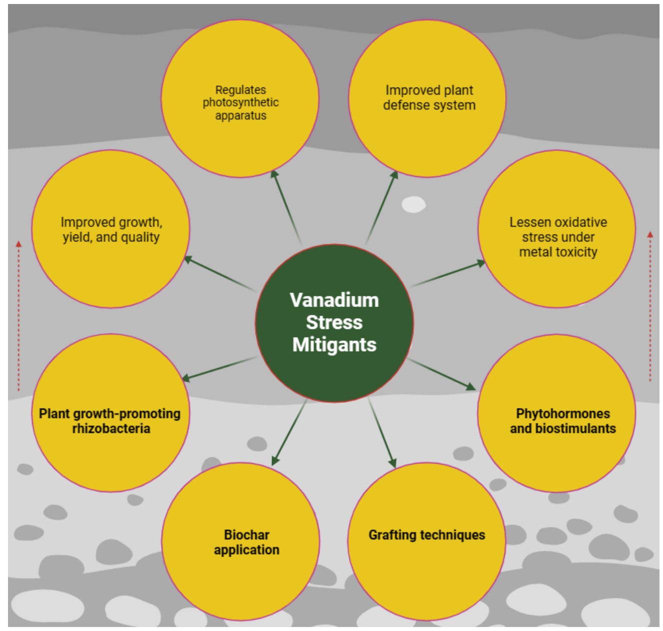

Figure 1: Different stress mitigants with potential against adverse effects of vanadium stress in plants.

The application of plant growth-promoting *Rhizobacteria* and bio-stimulants for enhanced vanadium resilience

An innovative method that serves two purposes is the utilization of plant growth-promoting rhizobacteria (PGPR) to increase productivity in crops under stress from heavy metals. One of the more hazardous possible inorganic pollutants that can contaminate soil, water, or air and make their way into the food system is a buildup of heavy metals (Singh et al., 2019). The issue is particularly bad in and around large, heavy-industry urban centres. Hence, plants have been shown to produce phytohormones as a coping mechanism for abiotic stressors. The potential for external use of phytohormones generated by microbes to boost plants' ability to withstand stress (Nazli et al., 2020). The method has also been documented as a potentially useful strategy to help crop plants develop stress resistance in harsh conditions. These bacteria can enhance plant development in addition to creating them through a variety of indirect as well as direct approaches (Zhu et al., 2023). Therefore, bacteria can alter how plants produce endogenous hormones, which could alter how plant tissues metabolize their resources. These microorganisms may be employed to stop the harmful consequences of stress linked to heavy metals (Khan et al., 2009). One of the sustainable methods for growing crops in unstable conditions is the application of PGPR during stress from metals (Ali et al., 2011). To increase agricultural yield and enhance soil and ecosystem strength, approaches utilizing biological genetics, computational biology, and modelling techniques should be developed to enhance plant-microbe relations (Yildirim et al., 2022).

Vanadium is a crucial metal in industrial processes, but excessive concentrations of it can be harmful to humans, animals, and plants (Chen et al., 2016). A considerable vanadium level escapes throughout the soil environment because of its diverse deployment in factories (Doklega et al., 2022). A wide class of chemicals known as "bio-stimulants" increases the efficiency with which plants absorb nutrients, enhances qualitative characteristics, and may even help plants develop a stress response (Trejo-Téllez et al., 2023). Plants that are bio-stimulated grow faster and are better able to withstand stress (Bartucca et al., 2022). Following numerous research, it has now been determined that these bio-stimulants play a part in lowering the toxicity of heavy metals by stimulating the antioxidant reflex (Fig. 1) (Gill et al., 2023; Sharaya et al., 2023).

CONCLUSION AND FUTURE IMPLICATIONS

Horticultural crops are highly threatened by vanadium-induced stress, which has negative effects on their growth, yield, and quality. There are several ways to reduce the oxidative stress and disruption of physiological processes occurring from vanadium toxicity. The potential approaches for suppressing vanadium toxicity in horticulture crops include the use of bio-stimulants, biochar, phytohormones, soil microbes, and plant growth regulators. The researchers and growers can work towards sustainable horticulture practices that lessen the negative impacts of vanadium-induced stress by putting these mitigation methods into practice.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that seem to affect the work reported in this article. We declare that we have no human participants, human data, or human tissues.

Author contribution statement

Riaz Ahmad: conceptualization, Data curation, Reviewing and editing. **Muhammad Usama Sabir:** Writing, Visualization, Validation.

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