



# Insights to proteomics and metabolomics metal chelation in food crops

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## Abstract

Metal pollution of water and soil ecosystems has been linked to stress and/or toxicity in plants, thus affecting the quality and productivity of food crops. This condition has further aggravated the essential food demand caused by the increase in the human population. Reports from previous studies have shown that correcting the noxiousness due to metal stress tolerance, requires several modes of action in the systemic, tissue, cellular, physiological, biochemical, and molecular levels in food crops which might be apparent in terms of enhanced productivity. The possible targets of the toxicity impact of metals in food crops are the MG (methylglyoxal) and ROS (reactive oxygen species) which could result in damage to the DNA structure, enzymes inactivation, protein oxidation, and lipids' peroxidation. This current review evaluates insights into proteomics and metabolomics of metal chelation in food crops with special effects on the toxicity, tolerance, and partitioning of metals towards better health. Detailed information on the biochemical and physiological mechanisms of plant stress from metal induction and tolerance was highlighted. The specific information of various tolerance strategies of food crops under trace element toxicity, the function of metabolites, proteins, and food crop hormones in stress tolerance to heavy presences of metal contents in plants is discussed. Information on the partitioning of trace elements in food crops was enlisted. The health benefits and possible risks from the consumption of trace metals in food crops were evaluated followed by recommending the future research directions.

**Keywords** Stress tolerance · Metal transportation · Transcriptomics · Metabolomics · Nutrient safety · Biofortification

## Introduction

It has been established that humans need at most twenty-two (22) elemental minerals for their overall well-being (Graham et al. 2007; White and Broadley, 2009). These minerals can be found in well-balanced diets. Conversely, it has been projected that over sixty percent (60%) of the world's population (6 billion) are iron deficient, thirty percent (30%) are zinc and iodine deficiency and fifteen percent (15%) are selenium

deficient (White and Broadley 2009). The deficiency of these essential elemental minerals is decreasing with increasing world population, because the current population estimates are about 7.9 billion as of 2021 with a growth rate of around 1.05% per year, speedily and ready to hit about 10 billion in the year 2050 (World population projects 2017).

Copper, magnesium, and calcium deficiencies are mainly common in developing and developed countries of the world (Thacher et al. 2006). These conditions have also been linked to crops cultivated in areas with poor mineral contents in the soil, inability of the soil to make available the soil nutrients (phyto-availability), naturally poor plant tissues that cannot translocate nutrients to areas needed, and lack of animal or fish products in human meals (Poletti et al. 2004; Graham et al. 2007). Mineral deficiencies can be addressed via the improvement of elemental concentration in eatable crops, biofortification, and dietary diversifications (Copenhagen Consensus 2004; <http://www.copenhagenconsensus.com>). However, different methods to boost the quality of

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food, mineral supplementation, and food diversification are recently being affected by several ecological factors.

Plants' response to abiotic stresses such as flooding, drought, and trace metals strains, have been validated to elicit about 70% global crop reduction and are considered the major stumbling blocks to crop production (Jewell et al. 2010). This is aggravated due to the upset in the balance between population growth and crop productivity.

At high concentrations, the essential metals become toxic to plants upon absorption from the soil. However, the uptake and utilization of these metals could be regulated by specialized cells in the plants (Srivastava et al. 2012; Fidalgo et al. 2013; Singh et al. 2016). Even more worrisome are the effects of non-essential metals like Hg, Al, Pb, Cr, and Cd which are noxious to plants, even at low concentrations (Hayat et al. 2012; Gill et al. 2013; Singh et al. 2016). The short-term effects on the plants include senescence, assimilation of nutrients, change in water balance, photosynthesis and growth inhibition, chlorosis, reduced biomass accumulation, and death. In the long run, however, the environmental persistence of the metals makes them accumulate in humans via the food chain (Anani and Olomukoro 2017; Anani and Olomukoro 2018a, b; Enuneku et al. 2018a, b; Enuneku et al. 2019).

Most plants, especially legumes and grains which are less expensive, are highly consumed because of the carbohydrates, oil, and protein contents therein. Legumes and grains generally can be grown in arrays of climatic factors. During the pre-growth period, they are significantly influenced by several non-living factors like drought (Alam et al. 2010; Mohammadi et al. 2012) and flooding (Komatsu et al. 2012a, b, 2013a, b; Nanjo et al. 2013). Thus, it is important to know the biological responses of plants to such stressors these factors viz drought, floods, and metals. This will aid in the improvement of the quality and quantity of crops.

The application of the “omic” instruments like proteomics and metabolomics have been long used as tools to enhance stress tolerance in crop breeding programs aimed at the development of agronomical and genetically desirable traits (Atkinson and Urwin 2012; Singh et al. 2016). In-plant improvement program, prioritizing the level at which certain flora species react to ecological stress shows their molecular adaptability to the abiotic factors. Fluctuation in the expression of the genes is influenced by induced stress and alteration of the metabolic process of the function and abundance of the cellular proteins (Hossain and Komatsu 2014). Therefore, a careful understanding of the mechanisms by which the protein structures are altered under certain ecological stress is very important in explaining plants' tolerance to injury and stress by the identification of new genes through biological sequencing (Hossain and Komatsu 2014).

Due to the lack of correlation between mRNAs' expression levels and the abundance of their corresponding

proteins, proteomic techniques provide one of the best options for the functional analysis of translated regions of the genome. Furthermore, several proteins undergo post-translational modifications such as removal of signal peptides, phosphorylation, and glycosylation, which are extremely important for protein function.

Modern bioinformatics and genomic sequence using complemented metabolomics and proteomics data offer a strong instrument in the characterization and identification of new proteins that will relatively enable plant species to adapt to serious environmental settings (Nanjo et al. 2012; Swigonska and Weidner 2013). In this context, this review evaluates the insights into proteomics and metabolomics metal chelation in food crops with special features of their level of toxicity, tolerance, and partitioning of nutrients in food crops towards better health.

### **Current reports on the insights into proteomics and metabolomics of metal chelation in food crops with special effects on the toxicity, tolerance, and partitioning of nutrients**

Singh et al. (2016) evaluated plants' tolerance to elemental metal stress using ionomics, metabolomics, proteomics, and transcriptomics. Singh et al. (2016) stated that metal toxicity to soil and water has severely affected plants' productivity and production. Metals in soil and water have counterbalancing noxiousness which has aggravated and worsened the tissues, cellular, physiological, biochemical, and molecular activities of plants. Singh et al. (2016) reported that elemental metal tolerance by plants in soil ecosystem can be upturned by the application of ionomics, metabolomics, proteomics, and transcriptomics using stressed free metabolites proteins that have inducible and transcriptional factors and also by the use of metallophytes; metal accumulating plants that have the abilities to regulate the incursion impacts in plants biological process. Singh et al. (2016) suggested that human activities that can influence the ecosystem negatively should be reduced. This will improve the global production and productivity of plants.

Vinocur and Altman (2005) investigated the current innovations in engineered flora tolerance to non-living ecological stress, their limitations, and achievements. Vinocur and Altman (2005) stated that biotic stress can be regulated by engineering monogenic traits in plants which are tolerance components that signal the pathways of the multigenic nature of plants. Thus, methods of flora engineering towards tolerance to heavy metals in soil involve the synthesis of structural and functional metabolites and proteins that confer plants tolerance to heavy metal stress. In addition, genes in plants that are metal responsive also show full and surprising

potentials that can be exploited for next generational studies using proteomics and metabolomics to combat recalcitrant metals for a free, sustainable, and better crop production and productivity.

Elemental metal noxiousness is one of the severe abiotic factors militating toward the health, nature, and nurture of plants. Methylglyoxal, and reactive oxygen species are severe factors from the accumulation of elemental metals that can result in the damage of the DNA structure, poor responses of enzymes, oxidation of proteins, and lipids peroxidation in plants (Hossain et al. 2012). On this note, Hossain et al. (2012) evaluated plant tolerance and the molecular mode of action of elemental metals, and the detoxification function of Glutathione to metal chelation, methylglyoxal, and reactive oxygen species. Hossain et al. (2012) stated that elemental metals that come in contact with living plant cells can be confiscated by GSH (glutathione), organic acids, specific bond ligands metals, and amino acids. That GSH being the main molecule of both the glyoxalase and antioxidant defense systems, is involved in both direct and indirect management of MG and ROS (methylglyoxal and reactive oxygen species) and the interaction of the plant cell products, therefore, shielding the plant from oxidative stress elicited by the elemental metals. Hossain et al. (2012) recounted that the mode of action by GSH and some of its enzyme metabolites like glyoxalase II, glyoxalase I, glutathione reductase, dehydroascorbate reductase, glutathione peroxidase, and glutathione S-transferase act coordinately and additively for the protection against methylglyoxal and reactive oxygen species damages and the biological restoration of the active and dividing cells of plants. In addition, GSH helps in the compartmentation, chelation, complexation, and detoxification of elemental metals in plants. This will boost the cellular and molecular adaptation of serious elemental metal stress in plants and ultimately decontaminate the probability of toxic elemental metals entering the food chain.

Rapid development and industrial boom have caused the introduction of several chemicals like toxic elemental metals into the environment which could cause severe changes in the biological structure and functions of plants that come in contact with them. This could affect their productivity and growth. In this context, Raia et al. (2021) reviewed the different biological methods for improving plants' (underutilized and neglected legumes) tolerance to toxic soil elemental metals. Many works have reported the environmental influence of toxic metals in terms of the biological, molecular, and physiological stress they portend to plants (Raia et al. 2021). The use of modern biotechnology techniques and tools like metabolites, proteins, transcription factors, and overexpressing genes that could be induced to manage ecological stress posed by metals, is in the limelight for better productivity and production of underutilized and neglected legumes. Raia et al. (2021) stated that biological

technology like CRISPR–Cas9, an advanced gene engineering tool can be used to detoxify absorbed toxic soil elemental metal via the process of phytoremediation. This technology aid to modulate or editing the gene expression of the legumes to enable them to combat abiotic factors militating toward the plant growth and the ability to use knockout and knockdown strategies in the management of toxic metal stress to them. In conclusion, Raia et al. (2021) suggested that research scientists working in the areas of flora science should focus more on effective methods in regulating gene-editing, riboswitches, and artificial promoters which will serve as an efficient technique for regulating plant genes against environmental stress. There is a need to explore further potential multidisciplinary methods such as synthetic and system biology to boost varieties of crops with high vigor and resistance to stress caused by toxic soil metals to underutilized and neglected legumes.

Morkunas et al. (2018) investigated the role of elemental metals in plant response to living environmental factors with specifics to the effects of hormesis. Morkunas et al. (2018) stated that the phenomena of hormesis have caused special interest in plant scientists to develop a basic framework that can elicit plants' abilities to respond to ecological and biological stress. The mechanism for defense plants uses to respond to various dosages of metal ions (hormesis) and living factors like disease-causing fungi and insects were discussed. Morkunas et al. (2018) also highlighted the ecological influence of metals on the ecological community of plants and the primary consumers like the aphids and herbivore insects.

In agronomic activities, the toxic accumulation of metals in soil is a serious ecological problem that has caused a serious threat to food security and safety. On this ground, Rizvi et al. (2020) evaluated the microbiological and induced phytotoxicity of toxic elemental metals on wheat plants. Elemental toxic metals found in soil at limits beyond the slated threshold have negative effects on plants like reduced soil efficiency, reduced soil fertility, and reduced physiological composition of the soil which can eventually affect the production of wheat, animals, and humans food chain. Therefore, the toxic elemental metal cause induced phototoxic problems. Due to the problem of threatened food security and safety, caused by metal toxicity in the soil, several agronomists have proclaimed the need to devise a sustainable means of correcting and preventing this unpleasant scenario for effective crop production. To mitigate these negative effects, some microorganisms like the PGPR (plant growth-promoting rhizobacteria) have been used to correct the effects of toxic metals in soil because they show promising and endowed features that could be used to manage soil toxicity caused by metal effects. Rizvi et al. (2020) stated that PGPR shows positive effects on the production of wheat even with soil polluted with high toxic metal, PGPR supplies

micro and macronutrients and also secretes dynamic biomolecules like MTS (metallothionein), melanins, and EPS. For effective wheat production, Rizvi et al. (2020) recommended a review on the mode of action of metal noxious to wheat and how to mitigate microbial remediation methods on wheat planting practices.

Schiavon et al. (2020) investigated the biofortification of Se (selenium) in food crops, their challenges, and their status in human health and nutrition. Schiavon et al. (2020) opined that Se is an important element for the correction of certain health deficiencies in mammals' diets. Naturally, plant store Se is a major point source to consumers. However, the amount therein is not enough to complement the daily human intake. To correct this, the biofortification of Se to crops is adequate to balance the daily health requirement. To unravel this, there is a need to understand the metabolic route of Se in edible plants as well as the positive influence of Se in human diets to enrich the food quality. Nanosized and optimized selenium, phytochemicals with microbial conjugates can be used to manage soil and plant against adverse biotic and abiotic conditions.

On this ground, biofortification of plants with Se is one of the best candidates for improving and stimulating the nutrition of crops under serious environmental challenges, especially during this period of COVID-19, where selenium plays an important role in the boosting of the physiological and biological activities of human against the dreaded diseases.

Chaudhary et al. (2019) evaluated the different ways plant proteins respond to ecological stress caused by heavy metals. Plants are usually susceptible to toxic metal ions which affect cellular materials like proteins thus interfering with the homeostasis of the non-native and native proteins leading to reduced viability of the plant cell. However, plants possess universal cellular systems that are tolerant which aid in the detoxification of toxic metals to improve plants' response to stress. Chaudhary et al. (2019) opined that proteins are made up of the chief workhorse of active cells. That the process of metal detoxification by these cells is via chelation of their ions with metallothioneins and phytochelatin in the cytosol, compartmentalization proceeds which takes place in the cell vacuoles, and the elimination and healing of proteins that were degraded and damaged by metal stress that fail to meet their innate conformations which finally lead to survival signs and death. Chaudhary et al. (2019) opined that this process is very important, because it plays a vital role in the allocation and ionic homeostasis as well as in the clean-up of MG and ROS caused by metal stress to plants. In addition, Chaudhary et al. (2019) stated that previous studies have indicated that in the core breakdown process of impaired polypeptides, the E3 enzymes are over-expressed in the autophagic initiation and UPS pathways, however, the mono-ubiquitination prevents the accumulation

of toxic metal in the plants. It is not clear the subsequent mechanisms involved in the regulation of metal accumulation. Chaudhary et al. (2019) suggested that novel strategies should be put in place to reduce the translocation and uptake of toxic ions in plants by the manipulation of their cellular proteins. This promising option will ensure possible food security and safety.

## Responses to noxious metal using various HSPs (heat shock proteins) in plants

Noxious ionic metals severely influence the homeostasis of cellular protein by interfering with the aggregation and folding processes of non-native and nascent proteins resulting in the reduction of cell sustainability in plants (Rodríguez-Celma et al. 2010). Plants react to pollutants in the environment like HMs (heavy metals) by stimulating the HSPs (heat shock proteins) genes when under stress. However, these HSPs act as a workhorse in the protoplasmic contents of the cells which aid to chelate toxic metals in the cytoplasm with metallothioneins and phytochelatin which is followed by metal compartmentalization, and then degradation of pollutants and cell repair (Rodríguez-Celma et al. 2010; Rai et al. 2015; Oono et al. 2016). Table 1 shows the plant responses to metal using various HSPs. The members of HSPs, the methods of identification, and examples of heavy metals were also highlighted.

## Specific information of various tolerance strategies of food crops under metal toxicity, their biochemical, physiological, and metabolic functions, as related to tolerance responses

Wiszniewska (2021) evaluated the influence of trace metal on plants using the priming methods. Wiszniewska (2021) recounted that plant tolerance to environmental stress is important to reduce the challenges to their effective productivity. Many plant species encountered developmental irregularities as a result of exposure to high or fluctuating noxious concentrations of metalloids and metals like Zn, Pb, Ni, Hg, Cu, Cd, As, and Al. However, plants have developed several modes of action which are activated with high efficiency and intensity to defend themselves from exogenous stressors. Wiszniewska (2021) recounted that primed floras have a high ability to adapt and survive under intense metal stress or counteracting multi-abiotic and multi-metallic stresses. The author suggested that priming can be applied routinely in horticulture and agricultural practices globally. However, inevitable pros exist using advanced bioengineering in the

**Table 1** Plant responses to metal using various HSPs (heat shock proteins)

| S/N | Species of plants   | Members of the HSPs   | Methods for identification of proteins  | Metals                 | References  |
|-----|---|---|---|------------------------|---|
| 1   | <i>America mantine</i> , <i>Chenopodium album</i> , <i>Kandella candeli</i> , <i>Arabidopsis thaliana</i> , <i>Populus alba</i> L., and <i>Lycopersicon peruvianum</i> L. | HSP17, HSP26.13p, HSP23p, HSP20, HSP21, and HSP17               | Reverse transcription polymerase chain reaction (RT-PCR)<br>Amplification, n-gel tryptic digestion and MALDI-TOF-MS analysis, Tandem Mass Spectrometry, Gene Structure Display Server 2.0, chloroplast chromatin immunoprecipitation, and Flash Fluorescence Measurements | Cu, Cd, Ni, and Zn     | Neumann et al. (1994), Naumann et al. (1995), Zhao et al. (2009), Lingua et al. (2012), and Haq et al. (2013)   |
| 2   | <i>Arabidopsis thaliana</i> , <i>Oryza sativa</i> L. and <i>Saccharomyces. Cerevisiae</i>   | ClpB-C, HSP101, and HSP104                                      | sqRT-PCR (Semi-quantitative reverse transcription) analysis, and polymerase chain reaction, Tandem MS (Spectrometry), and Fluorescence Correlation Spectroscopy   | As, Co, and Cu         | Sanchez et al. (1992), Agarwal et al. (2003), Singh et al. (2012), Mishra and Gover (2014),   |
| 3   | <i>Oryza sativa</i> , <i>Solanum lycopersicum</i> , <i>Arabidopsis thaliana</i> , and <i>Lemna gibba</i>  | HSP81-1, HSP82, HDP81.2, HDP89.1, HDP88.1, HDP88.4, and HDP81.3 | Tandem liquid chromatography mass spectrometry, Stationary-phase YPDA (yeast peptone dextrose adenine) Cultures, Protein electrophoresis, and sodium dodecyl sulfate polyacrylamide gel   | Cd, As, Cr, Pb, and Cu | Sanchez et al. (1992), Millioni et al. (1997), Haralampidis et al. (2002), Akhtar et al. (2005), Chakrabarty et al. (2009), Goupi et al. (2009), Song et al. (2013), and Oono et al. (2016) |
| 4   | <i>Chlamydomonas acidophila</i> , <i>Arabidopsis thaliana</i> , <i>Solanum lycopersicum</i> , and <i>Oryza sativa</i>   | HSP60, Cpn60-B, and cpn60 <sup>s</sup>                          | PCR (polymerase chain reaction) and agarose gel electrophoresis and real-time quantitative PCR (qPCR)   | Zn, Fe, Cd, and Hg     | Sarry et al. (2006), Spijkerman et al. (2007), Rodríguez-Celma et al. (2010), and Chen et al. (2012)  |
| 5   | <i>Solanum lycopersicum</i> , <i>Suaeda salsa</i> , <i>Populus alba</i> L. and <i>Oryza sativa</i> ,  | HSP68, BiP HSP70, and HSP70                                     | Feature extraction methods, salt/alkaline extraction method, and reverse transcriptions and total (T) RNA extraction  | Ag, Zn, Cu, and Hg     | Chakrabarty et al. (2009), Chen et al. (2012), Lingua et al. (2012), Liu et al. (2013), and Rai et al. (2015)   |

induction of effective biochemical genes towards the management of metalloids and metal stresses in plants.

Ghori et al. (2019) in a review evaluated the positive response of plants towards metal stress. Ghori et al. (2019) recounted that elemental metals like As, Hg, Zn, Cd, Co, Ni, Cu, Mn, and Fe in high concentrations have been linked to serious human activities which have caused several problems to plants in the ecosystems. Although, most of these metals are important micro-nutrients that are responsible for the metabolic and physiological activities of plants. However, when the concentrations exceed the normal background level, they become detrimental and affect the plant indirectly or directly. Nonetheless, plants have developed many mechanisms to combat ecological stressors. The mechanisms are important in bringing an internal balance of the metabolic activities that take place therein, regulate the detoxification of the metals, and initiate stress response that serves as a defense. This cellular response is exclusively involved in metal ions sequestering, chelating, and compartmentalization in the vacuoles thus ensuring total detoxification. Ghori et al. (2019) stated that although these processes are effective, oxidative stress is well seen in the active cells. Based on this outcome, the cells secreting proteins are initiated thus signaling antioxidants, heat shock protein molecules, hormones, and stress-associated proteins.

Globally biomagnification and bioaccumulation of toxic metals by plants have become worrisome because of the possible health impacts they portend. Because of this, Emamverdian et al. (2015) did a review of the mechanisms of defense plants used to combat heavy metal stress. Emamverdian et al. (2015) stated that the levels of toxic metals in plants can influence many important biomolecules that of cellular base like DNA and proteins, which can result in serious physiological, metabolic, and morphological problems ranging from the degradation of proteins, peroxidation of lipids, and shoot chlorosis.

In a swift response to this, floras equip themselves with a repertoire of the mode of actions to combat the toxicity of the heavy metals. Some of the key mechanisms are the formation of MTs (metallothioneins) and/or PCs (phytochelatins) which aid in metal chelation at the intracellular and intracellular levels. This is followed by the decontamination of metal ions from the vacuole's sites via sequestration of complex ligand elemental metals. In addition, there is a secretion of the non-enzymatically compound like Pro (Proline) which aid in the strengthening of the decontamination ability of the antioxidant enzyme(s) that is intracellular.

It is worthy of note that a crucial additional substance of the defense mechanism of the plant is the biological association with AM (*Arbuscular mycorrhizal*) fungi. These fungi aid in the immobilization of toxic metals and reduce the efficiency of their biological uptake through metal ions binding to the cellular wall of the fungi's hypha, thus excreting

different biomolecules of extracellular origin. The fungi also aid to boost the activities of the mechanisms of defense in plants. In conclusion, Emamverdian et al. (2015) recommended the total understanding of the mechanisms plants use to combat toxic metals to alleviate possible impacts. There is also the need to input sustainable agriculture and horticulture practices when applicable thus improving the soil organic materials which in turn spur the ecological and biological association of AM and the plants. Furthermore, the selection and examination of good species of AM can also boost the mechanisms of plant response to toxic elemental metals.

Bücker-Neto et al. (2017) in a review evaluated the responses of plant hormones to toxic metals as well as their interactions. Bücker-Neto et al. (2017) recounted that metals are non-biodegradable substances that are naturally found in the ecosystem. Human activities since the inception of the industrial revolution have increased the background concentrations leading to soil contamination and reduction of plant yield and losses. To understand how plants respond to metal stress, physiological and molecular cues are important in the determination of their mechanisms. Bücker-Neto et al. (2017) opined that plant hormones like ethylene, brassinosteroid, auxin, and the abscisic acid act as signaling systems in alleviating and in the defense against metal noxiousness.

Sytar et al. (2019) did a review of plant hormone priming in regulating toxic metal stress to plants. Sytar et al. (2019) stated that plant hormones act as chemical envoys that aid in the regulation and sustenance of abiotic and biotic stresses. Therefore, plant hormones are well known for their immense controlling role in the development and growth of cellular materials and tissues. Metals play a significant role in plants' development and growth as micro and macronutrients, however, at higher concentrations, they are toxic to them and humans in the long run along with the food chain structure. Sytar et al. (2019) stated that there is a need to proffer an economical and ecofriendly approach towards the effective tackling of these ecological problems. That collective methods like the utilization of exogenous plant hormones like gibberellins, cytokinins, and auxins and the use of physico-chemical approach, can yield positive effects in the control of the assimilation, nitrogen metabolism activities, cell division, and the ascorbate–glutathione cycle, that can boost the growth and productivity of the plant. In addition, salicylic acid, ethylene, and brassinosteroids have been recounted to improve the concentration of photosynthesis.

Peroxidation of lipids, reduction of the ROS levels and enhance the antioxidant systems when using in the effects of toxic metals. Sytar et al. (2019) suggested that hormone primed plants are known for their effective tolerance to abiotic factors like metals. In addition, chemical primed plants show good adaptation to stress and improved physiology. In conclusion, Sytar et al. (2019) opined that primed flora hormones

have exogenous effects when utilized to control environmental conditions like toxic metals that influence plant development and growth. The use of bio-formulations as suitable tools for polluted soil reclamation is suggested as a sustainable instrument for improving crop quality and productivity in areas of toxic elemental metals.

Mostofa (2015) in a biological study evaluated the biochemical and physiological mechanisms linked to Cu-stress in rice seedlings with induced Tre (trehalose). The results showed that rice seedling pretreatment with Tre significantly improved the endogenous level of Tre and mitigated the influence of the noxious effects of Cu on the growth and photosynthetic-related activities. This enhanced tolerance elicited by Tre is linked to its capacity to decrease the uptake of Cu and reduce the induction of the Cu as related to the oxidative damages, malondialdehyde, and the ROS accumulation in the plants stressed by Cu. It was noticed that Tre countered the increase of glutathione and proline induced by the Cu but significantly boost the redox potential and ascorbic acid status in the plants. The enzymes and the antioxidant activities were improved by the pretreatment of the rice plants with Tre when exposed to a high concentration of Cu. In addition, there were improved actions of glyoxalases 11 and 1 related to the decrease in the concentration of methylglyoxal when used as Tre pretreatment. The findings of the study revealed that Tre is important in the modification of endogenous Cu uptake in rice plants thus decontaminating the potent noxiousness it portends. This foundation from the findings shows the importance of the biosynthesis of Tre in genetic engineering.

Trace metals are very important to the development and growth of plants. However, when in a concentration greater than normal, they portend potential toxins. Andresen et al. (2018) evaluated the metabolism of trace metals (Zinc, nickel, Molybdenum, manganese, iron, and copper) in plants. Andresen et al. (2018) stated that anthropogenic and natural activities cause a vast increase in the concentration of trace metals in the soil even to extent of high deficiencies levels. However, there is a need to know how plants respond to detoxification, toxicity, deficiency, physiological routine, speciation, sequestration, transport, and uptake of trace metals. Andresen et al. (2018) opined that metal toxicity, deficiency, and usage are interconnected mechanistically. The absorption of toxic metals can impede the metalloproteins, biochemistry, physiology, metabolism, and the expression of the gene activities in plants.

## Gene pathways and response in metal stress in food crops

The sessile state of plants regularly exposes them to several degrees of ecological stressors like heavy metals that might result in overproduction of ROS and oxidative stress that

could lead to the constant disturbance of the physical and chemical structures of the deoxyribonucleic acid as well as the induction of the genotoxic and cytotoxic stresses therein. Such situations can affect the plant's yield and health. Table 2 shows the antioxidant gene pathways and response in metal stress in food crops/plants.

## Proteins and DNA genes responsible for plants tolerance to metal stress

Environmental and biological stresses are the major factors militating against plant development and growth. Toxic metals generally affect cellular homeostasis thus interfering with the biological functions of plants. Hasan et al. (2017) evaluated flora proteins' responses to toxic metal stress. Hasan et al. (2017) opined that plant proteins are the main workhorses to biological active cells. The workhorses aid in the chelation or removal of ionic metals in the cytosol or vacuoles via tonoplasts transporters with the means of metallothioneins and phytochelatin. This is preceded by metal compartmentalization, repair of proteins that are damaged by heavy metal influence, and the degradation or removal of proteins that did not achieve their natural conformation towards tolerance to stress from the metal influence. The proteins that were damaged are removed from the cell by the initiation of ERQC and ERAD system and machinery, leading to UPS (proteosomal) and/or autophagic breakdown.

Li et al. (2020) in a biological experiment, evaluated the protein expression, duplication, phylogenetics, identification profile assessment of Arabidopsis, and rice tolerance to toxic metal stress. Plants' exposure to toxic elemental metals is a serious ecological problem. Nonetheless, plants have developed different strategies to boost their efficiencies towards metal tolerance from the soil. Li et al. (2020) opined that HMPs (heavy metal-linked proteins) assist in the detoxification of noxious metals in plants. In the biological experiments, Li et al (2020) examined 55 and 46 HMPs in Arabidopsis and rice correspondingly, identified them as AtHMP 1–55 and OsHMP 1–46 based on their loci in the chromosomes. For both plants, the HMPs were subdivided into 6 clades as related to their metal-linked characteristics (HMA) domains. The results from the studies indicated that the HMP motifs and gene structures differed immensely among the various classifications. There was an increase in the duplication and collinearity of the HMPs. Further analysis using the cis-element showed variations in the factors of the transcription as regulated by the HMPs. There was an eight OsHMPs' profile of expression in the tissues of the rice as shown by the analysis. OsHMP37 showed higher expression than the other seven genes. However, in the region of the roots, OsHMP28 was exclusively expressed. On the other hand, nine AtHMPs were highly presented in Arabidopsis

**Table 2** Metabolic data involving antioxidant gene pathways and response in metal stress in food crops

| S/N | Plants source   | Antioxidant genes and metabolic pathway(s) | Metabolic stress  | References                                   |
|-----|---|--|---|--|
| 1   | <i>Anabaena</i> species                                     | Alkyl hydroperoxide reductase              | It enhances plant tolerance against Cd and Cu by improving the scavenging of reactive sulphur and H <sub>2</sub> O <sub>2</sub> species                                     | Mishra et al. (2009)                         |
| 2   | <i>Vigna aconitifolia</i>                                   | Δ1-pyrroline-5-carboxylate synthetase      | Acts as an antioxidant under Cd stress to therefore improves the plant tolerance to toxicity  | Siripornadulsil et al. (2002)                |
| 3   | <i>Paxilus involutus</i>                                    | MT1  | Improves the tolerance of plants to Hg  | Bellion et al. (2007) and Ruiz et al. (2011) |
| 4   | <i>Arabidopsis</i> species                                  | PCs and PCS1                               | Improves the plant's tolerances to Cu and Cd stress by the stimulation of phytochelatin   | Li et al. (2004) and Chaurasia et al. (2008) |
| 5   | <i>Allium sativum</i>                                       | Serine acetyltransferase                   | Improves the plant's tolerance to As and Cd toxicity by the production of glutathione and phytochelatin metabolites   | Guo et al. (2008)                            |
| 6   | <i>Thiaspi caerulescens</i> and <i>Thiaspi goesin-gense</i> | TcPCS1 and Serine acetyltransferase        | Improves plant's tolerance to Cd, Co, and Ni stress by enhancing the activities of CAT, POD, and SOD based on the enhancement of glutathione and reduced lipid peroxidation | Freeman et al. (2005) and Liu et al. (2011)  |
| 7   | <i>Brassica rapa</i>  | GR   | It enhances plant's tolerance the accumulation of Cd  | Kim et al. (2009)                            |
| 8   | <i>Brassica juncea</i>                                      | CAT3                                       | It improves better roots and seedling growth under cd stress  | Gichner et al. (2004)                        |
| 9   | <i>Festuca arundinacea</i>                                  | APC  | Enhances plants' tolerance to oxidative stress caused by As, Cd, and Cu   | Lee et al. (2007)                            |

with high transcript concentration in all organ parts. It was noticed that all most all designated OsHMPs differed significantly and were expressed in different tissues exposed to different metal strains. Only OsHMP22, OsHMP18, and OsHMP09 revealed significant upper expression concentrations in all tissues in metal influence. Contrary, the majority of the chosen AtHMPs showed consistent expression at various tissues under metal stress. It was noticed that the different genes AtHMP46, AtHMP35, AtHMP31, AtHMP25, AtHMP23, and AtHMP20 were significantly expressed in the roots and leaves under metal stress. Findings from the study showed that the characteristics of the HMP elucidated dicotyledonous and monocotyledonous plants as perfect tools for HMPs for future study.

Zhang et al. (2017) in a biological study, investigated plant protein tolerance OsMTP11 as potent transporter of manganese in rice plants. Zhang et al. (2017) recounted that MTPs (metal tolerance proteins) belong to the gene family of CET (cation efflux transporter) that is found distributed in plants. These genes play an essential part in the tolerance and homeostasis of the biological functions of plants. From the results, Zhang et al. (2017) stated that OsMTP11

showed universal and constitutively expressed in various tissue parts of rice plants. The examination of the heterologous appearance in yeast revealed that OsMTP11 was sensitive and complement transmuted strains to manganese. In addition, it complemented metals like Ni and Co. The real-time analysis (RT-PCR) showed that the expression of OsMTP11 genes was improved in 4 h when treated with Mn, Ni, Zn, and Cd thus suggesting the effective roles and involvement of OsMTP11 in stress-related tolerance responses. Further analysis using the GUS genes (promoter transgenic assays) and the messenger RNA, revealed that OsMTP11 was effectively expressed in the tissue of the rice. The methylation assays showed that the genomic activities of the rice DNA treated with Mn, Ni, Zn, and Cd expressed a reduction in the methylation concentration found in the promoter sites of the OsMTP11. This induction is a result of stress from the metals. The GFP (green fluorescent protein) analysis showed that the OsMTP11 was bonded to the epidermal cells at the cytoplasm. Meanwhile, the membrane of the vacuoles showed improved green fluorescent protein signals with consistent cation sequestration. The findings from this study showed that DNA methylation is the main regulating factor



via the epigenetic model of actions and elicited manganese transport and metal detoxification in the rice plant. This will offer special insights into the molecular pathway of manganese and other reposition, transport, and absorption process of metals in rice plants.

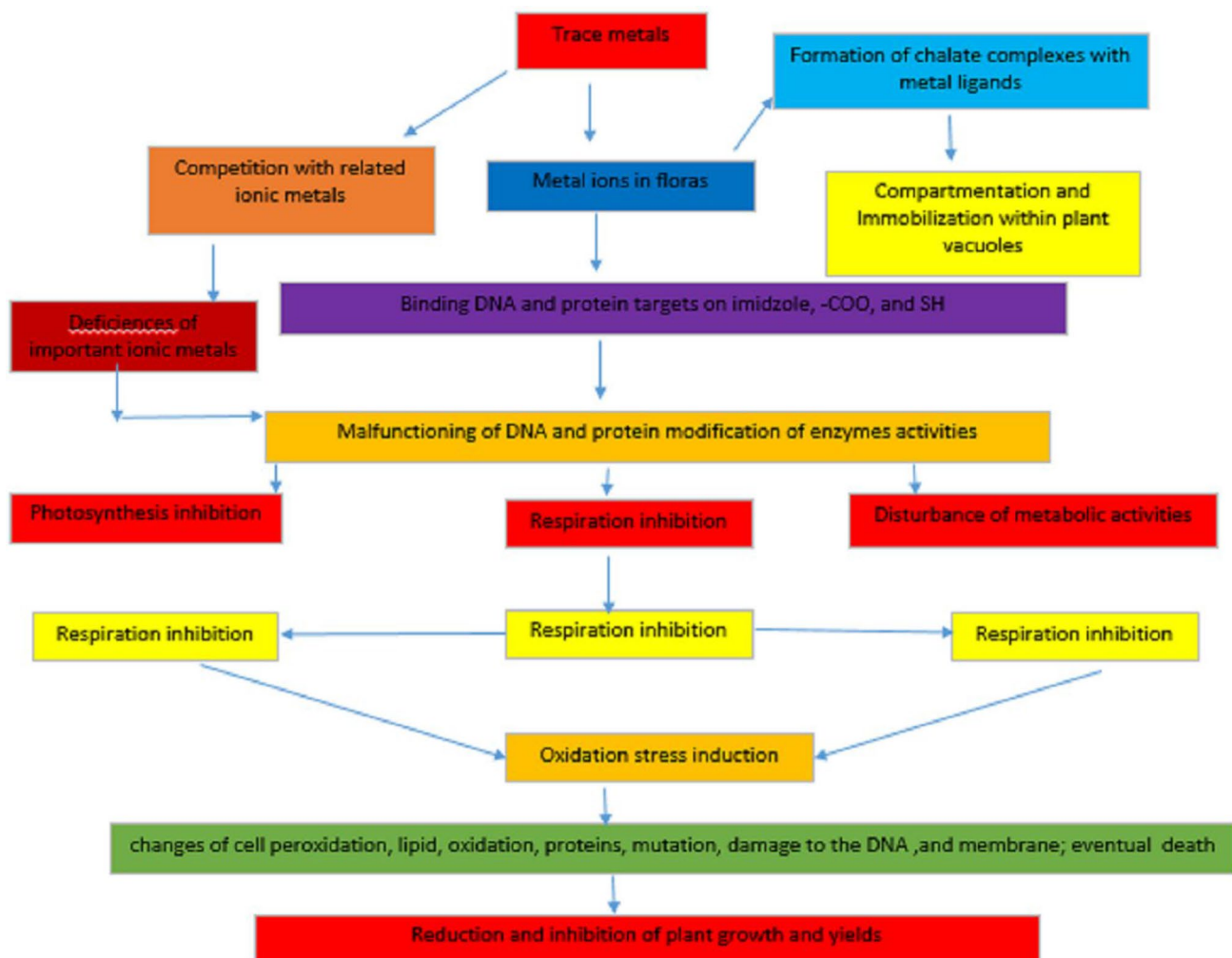
### Schematic of the molecular and biochemical mode of actions of toxic elemental metals in higher plants

The ability of plants to tolerate HMs influence is the function of their physiological, molecular and biochemical mode of actions. Different species of plants have developed several mode of actions to adapt to metal stress. Figure 1 shows various compartmentalization processes that

higher plants employ when toxic elemental metals induced damage and ROS to the growth and development of their cellular contents.

### Derived health benefits and possible risks from the consumption of the trace elements in food crops

There are some elements required by human bodies in a relatively small amount whose absence could result in malfunctioning of some of the vital human systems and eventually death in some extreme cases due to the indispensable role of the elements in the metabolic processes of the organisms (Bhattacharyya et al. 2014).



**Fig. 1** Possible molecular and biochemical mode of actions of toxic elemental metals induced damage and ROS to the growth and development of higher plants

## Classes of trace elements

Various attempts and criteria have been put forward in the classification of trace elements. One of the major is the world health organization (WHO) 1973 classification of the trace elements. According to WHO, there are three major groups of trace elements:

- (i) Essentials elements: such as selenium, zinc, iodine, copper, cobalt, molybdenum, and manganese
- (ii) Possibly essential: these are the elements considered to be probably essential
- (iii) The potentially toxic elements

Some elements are vital components of enzymes such as selenium, iron, and zinc. They enhance the attraction or subtraction of molecules and facilitate their breakdown and interconversion to their specific end products. There are also a few of these elements that help in donating or accepting electrons during redox reactions.

Similarly, Frieden (1985) proposed the classification of elements into the trace, micro, and ultra-trace elements based on the quantity found with the tissue.

Based on the classification, the elements were groups as:

- (i) Essential trace elements: such as copper, manganese, zinc, molybdenum, boron, and cobalt
- (ii) Probable essential elements: fluorine, vanadium, chromium, nickel, and selenium
- (iii) Physically promotive category of trace elements: lithium, titanium, tin, and silicon.

These elements play their specific and related roles in biological systems.

## Copper

Copper is useful in the metabolic processes of the body by enhancing the proper functioning of vital enzymes. The solubility of copper compounds is enhanced by acidic conditions which aid their ease incorporation into the food chain. The toxicosis of copper is relatively rare in plants when compared to animals. In animals and man most especially, the toxicosis is mainly induced through environmental contents in genetically abnormal individuals. The availability of copper is mostly in milk and its products, dried fruits, liver, and shellfish (Deleves 2009). The content in plants on an average basis varies from 4 to 20 mg of copper each kg of dry weight. There is the presence of 100 mg copper in an average adult human with a weight of 70 kg while the requirement on daily basis is 2–5 mg of which the absorption of 50% of this occurs

in the gastrointestinal tract (GIT). The accumulation of copper occurs in the brain, liver, and kidney when compared to the other parts of the body. For plasma copper, about 90% is connected to ceruloplasmin, while 60% of red blood cells is held to superoxide dismutase (Prashanth et al. 2015).

## Iron

The overall body composition of iron is 3–5 g out of which over 75% is present in the blood, while others are in muscles, liver, and bone marrow. Heme is a substance that containing majorly iron. It is present in myoglobin, hemoglobin, cytochrome while certain enzymes are linked to iron such as catalases, xanthine, tryptophan, glucose 6, dehydrogenase, cytochrome A, B, and C, and choline ( Vasudevan and Sreekumari 2007).

The daily body requirement of iron is 1–2 mg which is usually provided from about 20 mg of iron from food. The absorption of iron in the gastrointestinal tract is usually reduced by oxalates and phytates. The transported form of iron is usually ferritin. The denatured form of ferritin is hemosiderin which is a brownish pigment that is commonly observed in the reticuloendothelial cells. Iron metabolism is special since it enhances the maintenance of homeostasis through the regulation of iron absorption, with no excretion. The absorption of iron is enhanced when it is depleted. Iron is vital in binding, transporting, and discharging oxygen in higher animals. Some other trace elements are useful in the control of relevant physiological processes through the aiding of molecular bindings to specific sites of receptors on the cell membranes (Saito, 2014).

The deficiency of iron results in serious diseases most significant is anemia. Iron deficiency anemia is associated with symptoms such as tiredness, microcytic hypochromic, achlorhydria, atrophy of epithelium, declined memory, and heart failure. Anemia has been identified as one of the primary causes of mortality among pregnant women (Gil et al. 2014).

Premalignant lesions in the mouth are one of the primary diseases associated with a decrease in the concentration of serum iron. The decrease in the content of iron at times could be due to its use in the synthesis of collagen. A drop in the content of iron in the oral tissue can bring about a fall in vascularity which can further enhance the percolation of arecoline (Tiwari et al. 2016).

## Zinc

Zinc has an average daily demand of 15 to 20 mg for each day. The average human body has a zinc content of 2 to 3 ng with about 99% found in the intracellular component of the body while others are found in the plasma. The excretion of zinc

occurs mainly in the intestine and pancreas where 2–5 mg is excreted each day. The excretion also occurs through the proximal tubule and sweat glands.

The role of zinc in biological systems cannot be overemphasized. The function could be grouped into three major parts which include regulatory, catalytic, and structural. It is needed for the catalytic processes of several enzymes. It is also vital in immune functioning, healing of the wound, cell division, synthesis of DNA and proteins. It is needed for an effective sense of smell and taste (Larsson et al. 2019). It is also valuable for proper growth and during the development of a fetus. It has also been reported to allegedly possess antioxidant potentials hence could be useful in speeding up the process of healing. Even at low content, zinc has been documented to possess antimicrobial properties. During pregnancy, there is a decline in the zinc content in plasma. The functioning of zinc depends on the enzyme metalloproteinase which is connected with the immune, reproductive and genomic quality of sperm. Zinc enhances the normal development of a fetus during pregnancy. It is useful in the metabolic functioning, differentiation, and proliferation of cells in mammals (Samarghandian et al. 2017).

## Chromium

About 0.006 g of chromium is present in an average human in the adult stage while the requirements on daily basis are 0.005 mg each day. Chromium is indispensable in the biosynthesis of glucose.

Deficiency in the content of chromium in the body brings about impairment of the tolerance of glucose, while high toxicity due to chromium could bring about pulmonary cancer, renal failure, and dermatitis. Best sources of chromium include spices, whole grains, and processed meat, while a relatively smaller quantity is present in vegetables and fruits. The excretion of chromium occurs mainly through urine, while there is a smaller quantity excreted through sweat, bile, and hair. After absorption, it is excreted primarily through feces (Choge 2020).

Chromium has been identified as a human carcinogen and taken in through inhalation and occupational area. Lung cancer has been associated with chromium in its hexavalent form. Most current details from researches have shown the presence of tumors in the skin of mice due to drinking of water containing hexavalent chromium. A high content of chromium in the plasma has been linked to hyperglycemia (Sun 2015).

## Cobalt

The absorption of cobalt compounds occurs through inhalation and oral path. The extent to which cobalt is absorbed through the gastrointestinal tract is determined by the dose

taken in, while the small doses are absorbed totally, larger quantities take a relatively long time for absorption. The storage of cobalt is usually in the red blood cells, liver, pancreas, kidney, and plasma. It is known to possess both useful and deleterious effects in physiological processes. Its usefulness is due to its connection with vitamin B<sub>12</sub> being a major component. It has been employed in the treatment of anemia and also pregnant women, because it aids the process of erythropoiesis. It also stimulates the production of red blood cells in healthy people (Prashanth et al. 2015).

Cobalt deficiency can bring about a disordered digestive system, fatigue, muscular and neurological problems. A cobalt deficiency also implies a decrease in B<sub>12</sub> and nerve damage. The effective formation of amino acids in the body is also affected by the presence of cobalt. It is also vital in the growth and improvement of the neurotransmitters which are vital for the proper formation of an organism. However, a high amount of cobalt in the body could bring about overproduction of erythrocytes, asthma, and the fibrosis of the lungs. Cobalt deficiency also brings about peripheral neuropathy.

## Molybdenum

Molybdenum is a major component of the protein molybdo-protein which is vital in the formation of enzymes. Some of the enzymes such as sulfite oxidase, dehydrogenase, aldehyde oxidase are all composed of molybdenum as a vital component. It is useful in the catabolism of purine and the synthesis of protein (Prashanth et al. 2015).

The effect of molybdenum and tungsten on collagen, when administered to mice in a study, revealed a decreased level of cross-linking. On that basis, it was deduced that there is no tropical binding of the metal and tungsten. The biological impact was as a result of competition with copper as well as interference with physiological cross-linking. Prolong application of doses of molybdenum in mice brought about a decrease in the stability of collagen. The growth of fibroblast was not affected when the mice were exposed to molybdenum powder (Hammer et al. 2015).

## Selenium

This trace element is a vital component of antioxidants, and a component of enzymes such as thioredoxin, reductase, and glutathione peroxidase. The selenium salts needed for proper cellular functioning in human bodies are poisonous in high doses. It has been reported that most microorganisms possess several enzymes made of selenium. A decrease in the content of selenium can bring about a rise in oxidative stress in the body tissues hence selenium dietary additives are vital

in the treatment of leukoplakia which is a premalignant lesion (Kuršvietienė et al. 2020).

## Conclusion and future recommendations

This current review evaluates the insights into proteomics and metabolomics of metal chelation in food crops with special effects on the toxicity, tolerance, and partitioning of metals towards better health. Plants' response to abiotic stresses such as flooding, drought, and trace metals strains, have been validated to elicit about 70% global crop reduction and considered as the major stumbling blocks to crop production. This is aggravated due to the upset in the balance between population growth and crop productivity.

Of recent, studies have been carried out to correct the highlighted problems. The application of the “omic” instruments like proteomics and metabolomics have been long used as tools to enhance stress tolerance in crop breeding programs aimed at the development of agronomical and genetically desirable traits.

On the aspects of current reports on the insights into proteomics and metabolomics of metal chelation in food crops, it was documented that toxic elemental metal tolerance by plants in soil ecosystem, can be upturned by the application of ionomics, metabolomics, proteomics, and transcriptomics using stressed free metabolites proteins that have inducible and transcriptional factors and also by the use of metallophytes; metal accumulating plants that have the abilities to regulate the incursion impacts in plants biological process.

The specific information of various tolerance strategies of food crops under metal toxicity, their biochemical, physiological, and metabolic functions, as related to tolerance responses were evaluated. It was suggested that priming can be applied routinely in horticulture and agricultural practices globally. However, inevitable pros exist using advanced bio-engineering in the induction of effective biochemical genes towards the management of metalloids and metal stresses in plants. The mechanisms are important in bringing an internal balance of the metabolic activities that take place therein, regulate the detoxification of the metals, and initiate stress response that serves as a defense. This cellular response is exclusively involved in metal ions sequestering, chelating, and compartmentalization in the vacuoles thus ensuring total detoxification.

On the aspects of the derived health benefits and possible risks from the consumption of the trace elements in food crops, it was stressed that some elements are vital components of enzymes such as selenium, iron, and zinc. They enhance the attraction or subtraction of molecules and facilitate their breakdown and interconversion to their specific end products. Most of the trace metals are regulatory, catalytic, and structural in their mechanisms. They are

needed for the catalytic processes of several enzymes and the biological functions of plants and animal cells.

Some essential proteins and DNA genes responsible for plants tolerance to metal stress like HMPs (heavy metal-linked proteins); AtHMP 1–55 and OsHMP 1–46 were discussed. It was observed that they offer special insights into the molecular pathway of metals in repositioning, transportation, and absorption processes in food crops.

Findings from this review showed that the characteristics of the insights into proteomics and metabolomics metal chelation in food crops have elucidated that dicotyledonous and monocotyledonous plants are perfect tools for HMPs (heavy metal-linked proteins) for future study. That heavy metal-linked proteins are essential for the detoxification of toxic metals in food crops using various biological mechanisms.

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## Declarations

**Conflict of interest** “The authors declare no conflict of interest”.

**Data availability statement** All information collated in this study was gotten from the Google search engine. Data were sourced therein via relevant references from different journals. We affirmed that apart from personal inputs, we reviewed series of scientific published works without laboratory-driven data. Hence, there is no applicability of data sharing and no new data were generated during this study.

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