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Impacts of Heavy Metal Toxicity on Plant Growth and Development: Insights into Physiological and Biochemical Responses

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Abstract- Heavy metal contamination poses a significant threat to plant growth and development, with detrimental effects on agricultural productivity, ecosystem stability, and human health. In this study, we examine how plants respond physiologically, biochemically, and morphologically to heavy metal toxicity to provide insight into the mechanisms underlying interactions between plants and metals as well as possible mitigating strategies. Heavy metals (HMs) such as chromium, cadmium, nickel, mercury, lead, and arsenic can enter plants through several different processes. Once inside, these metals interfere with vital physiological functions including photosynthesis, food intake, and water interactions. Heavy metals cause oxidative stress at the biochemical level, which results in the production of ROS and lipid peroxidation. These processes harm cellular constituents and interfere with metabolic processes. Furthermore, the morphology of plants is altered by heavy metal poisoning, which has an impact on root growth, leaf shape, and reproductive development. Plants have developed several defines mechanisms against heavy metal stress, despite the metals' harmful effects. These defines mechanisms include metal sequestration, chelation, and detoxification by complication with PC's and MET'S. It is essential to create sustainable solutions that include these plant responses to reduce the toxicity of heavy metals to plants and the environment. This paper highlights the need for interdisciplinary research efforts to address this pressing environmental issue by summarizing the state of the art upon the impacts of toxic heavy metals on the development and growth of plants.

Keywords- Heavy metal toxicity, metal uptake, oxidative stress, phytoremediation, plant-metal interactions, human health implications.

I. INTRODUCTION

HM pollution is a major problem these days. They are mostly responsible for soil contamination due to their toxicity and environmental endurance. HMs are found in soils due to a variety of causes, including sewage waste, farmyard manure, air deposition, fast industrialization, and widespread utilization of synthetic fertilizers (M.R. et al., 2021). Because they are sessile, plants are subject to a variety of environmental challenges throughout their life cycle. In recent times, heavy metals, or

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HMs, have become more significant among these stresses (Hussain et al., 2021). The functions and chemical characteristics of the heterogeneous group of elements known as heavy metals vary. Most heavy metals in the Periodic Table are transition elements. Heavy metal elements are defined as having a particular mass above 5 g cm2 (S.S. Leonard et al., 2004). The group of metalloids and heavy metals known as "heavy metals" as a whole have a density of atoms greater than 4000 kg/m3 (M. Edelstein et al., 2018). Of all the elements found in nature, 53 are categorized as heavy metals (HMs), and most of them don't participate in any kind of metabolic process in plants (Rebello et al., 2021). There are two types of heavy metals: non-essential (Cd, Ni, As, Hg, Pb) and essential (Mn, Mo, Cu, Zn, Ni, Fe). Essential heavy metals help the body's metabolism function. For example, copper is necessary for the production of hemoglobin and the metabolism of carbohydrates, yet excess amounts of these metals can harm cells, Similar to how many heavy metals are necessary for plants, these metals likewise function as cofactors, initiate enzyme reactions, exhibit ductility, and conductivity, and maintain cation stability. However, these metals exhibit toxicity when present more than the necessary concentration. The following heavy metals (HMs) impact about 20 million hectares (hectares) of land: copper, cadmium, chromium, lead, nickel, arsenic, and mercury. According to the Agency for Harmful Substances and Disease Registry (ATSDR), plants and humans are severely harmed by the As, Pb, Cd, and Hg four heavy metals (HMs) (S. Mansoor et al., 2020). Both macro and micronutrients, in sufficient quantities, support the activity of important enzymes and control metabolic processes such as sugar metabolism, protein modifications, DNA synthesis, photosynthesis, and redox equilibrium. Higher quantities of these, however, show toxicity and have the potential to be fatal for all living things, including animals and animals (Tiwari et al., 2018). The dispersion of these heavy metals has been disrupted by the rise in human activities such as industrialization, fertilizer application, mining, modern farming methods, broad groundwater irrigation, and sewage disposal. As a result, these HMs have accumulated in certain areas (Yu et al., 2014). In general, they have the potential to infiltrate plant systems and contaminate the food chain, which poses a serious risk to food safety and quality. Popular agricultural products like cereals, fruits, vegetables, and seafood have been shown to contain heavy metals.While soil contamination has an over-standard rate of 16.1%, the heavy metal (HM) over-standard rates. The relative percentages for Cr, Cd, As, Pb, and Hg are 1.10 percent, 1.5 percent, 1.6 percent, 2.7 percent, and 7.0 percent. (H. Zhao et al., 2022). while the ideal environmental conditions allow for the optimal concentration of these vital nutrients for sustainable plant development, these minerals can enhance many different cellular functions in plants, such as the synthesis of pigments, maintenance of ion balance, control of genes, respiration, the activity of enzymes, metabolism of sugars, photosynthesis, nitrogen fixation, etc (S. Hembrom et al., 2020). However, their intense bioavailability primarily causes oxidative bursts that cause various Plants to undergo physiological and metabolic changes, as listed in Table 1 (K. Bashir et al., 2016). The majority of these studies have looked at how plants subjected to HM stress affect OMICS techniques such as metabolomics, genomics, transcriptomics, proteomics, and genomic. By decreasing their absorption, compartmentalizing into vacuoles, sequestering through phytochelatins (PC)/metallothioneins (MT), and triggering antioxidant defense, some plants may withstand a modest concentration of HM(s). Activating the antioxidant defense system is a key tactic to counteract the negative impacts of stress circumstances, The production of production is one of the most common effects of stress situations on plants. Nonetheless, the effectiveness and onset of a particular defensive response are dependent on the kind and species of Heavy metals, their level, and the duration of exposure (Hasan et al., 2017). Most of these HMs have already been absorbed by the soil. Conversely, prolonged exposure to heavy metals can result in bone fractures and lung cancer in humans. The usage of common foodstuffs contaminated with heavy metals (HMs), such as fruits and vegetables, has raised serious concerns about human health in recent decades. Pb, Cd, and As are quickly taken up by the chain of food.

Because lead and cadmium accumulate in tissues quickly, they can have serious negative effects on renal function, the cardiovascular system, the auditory system, and developmental retardation in children. Compared to adults, children are more vulnerable to these medications (S. Hembrom et al., 2020). Therefore, it's critical to understand how heavy metal toxicity affects crops to create a scientific approach to boosting crop productivity in heavy metal-polluted soil, which will become more widespread shortly. The goal of this work was to integrate the most recent understanding of the plant stress responses caused by the presence of heavy metals (HMs) in terms of their structure, physiology, and metabolism to reveal the molecular foundations of HM toxicity and tolerance in plants.

Table 1: Minimal concentrations of dangerous heavy metals in soil and crops (Bharti et al., 2022).

Heavy Metals (HMs)	Limitation in soil (ppm. d. wt.)	Crop range (ppm d. wt.)
Pb	2-200	0.1-10
Cd	0.01-0.7	0.2-0.8
Ni	10-1000	1.0
Hg	0.01-0.2	0.005-0.02
As	0.1-40	0.01-5

II. OCCURRENCE AND SOURCES OF HEAVY METALS

According to a specialized study, the accumulation of heavy metals, in soil may cause a decline in soil fertility and agricultural output, as well as potential harm to human and animal health. Pb, As, Cr, Zn, Ni, Cd, Cu, and other heavy metals (HMs) are often found in soil conditions as pollutants. This kind of contamination is widespread, typical in the soil surroundings, and hazardous from a biological standpoint. According to the Environmental Protection Agency (EPA), the four most dangerous substances in the environment are lead, mercury, cadmium, and arsenic. Human production activities including chemical manufacture, fertilizer use in agriculture, and mineral mining are the major sources of heavy metal (HM) accumulation in soil. Many studies indicate that natural sources of metallic substances in the natural world are often not as concerning as human activities.

Fig. 1. Various sources of heavy metals (HMs) include wastewater, mining, waste, cars, plastics, nano fertilizer, and waste mining. (Source: Figure generated by author)

Natural Occurrence: Most people think that the most common locations for heavy metals to be found are in igneous or sedimentary rocks. The primary source of heavy metals (HMs) in soils is the parent material. Sedimentary rocks comprise around 5% of the planet's crust, with igneous rocks accounting for the other 95% (N. Sarwar et al., 2016). Because HMs are generated in the crust of the earth, they naturally appear in the soil as a consequence of erosion. Heavy metals are derived from rocks and can contaminate the soil environment through a variety of natural processes, including leakage, subsidence, volcanic eruptions, microbiological activity, agronomic activities, and surface winds.

Anthropogenic activity: Human-caused frequently indicates having human roots. Higher levels of heavy metals (HMs) are caused by human-caused processes including mining and smelting, burning fossil fuels for energy, getting rid of garbage from cities, using pesticides and fertilizers, and irrigating sewage (A. Khan et al., 2023).

Agricultural practices: Both sectors, especially in locations near cement and electroplating operations, contribute to the contamination of plants and soil with heavy metals. Animal dung, fertilizer, insecticides, wastewater, and other

materials are among the many potential sources in the area of agriculture. Pesticide application that is too careless puts animals and other non-target creatures in grave danger because it allows the toxins to bioaccumulate in food chains. Long-lasting pesticide residues can be found in plant components, soil, water, and air (R. Xiao et al., 2017).

Industrial application: The environment is exposed to heavy metals due to growing human activity, especially industrial advancements. These pollutants accumulate in the soil over time, particularly in places that are industrializing quickly (Y. Jin et al., 2019). Heavy metals come from a few industrial sources.

Mercury: Man-made emissions, gold mines, coal combustion, and geothermal activity are its sources. Mercury is also present in dental amalgam, medical waste, plastic, and scientific items like thermometers and thermostats. The amount of mercury present in the environment rises with the usage of fertilizers and pesticides containing mercury (F.R. Cifuentes et al., 1996).

Cadmium: The primary sources of cadmium emissions are Fossil fuel combustion, cement manufacturing, nickel-cadmium batteries, coatings, and plating. Additionally, it emanates from household garbage and industrial pollution. The weathering of rocks by volcanic eruptions, dust storms, and erosion are examples of natural processes that raise the levels of Cd. About 20,000–24,000 tons of CD are consumed worldwide each year (Sanjeevi et al., 2011).

Lead: Mostly produced during lead-acid battery recycling, ore processing, and mine operations. In battery manufacturing facilities, lead is mostly utilized. Automotive exhaust, plumbing pipes, industrial waste, and paint with lead content can all leak lead into the air. Sea salt spray and volcanic eruptions are two other natural phenomena that increase lead levels in the environment (Zulfiqar U et al., 2019).

Nickel: Natural causes of nickel emission include wind, rock weathering, and wildfires. Ni is also released into the environment by anthropogenic operations including casting and battery production facilities. It is also released from cooking utensils made of stainless steel and tobacco (Sanjeevi et al., 2024).

Arsenic: Arsenic is mostly emitted by a variety of human-caused processes, including mining, burning fossil fuels, smelting, and the use of chemotherapy drugs. Additionally, paints and food preservatives emit it (Anuradha et al., 2011).

III. PLANTS' SUSCEPTIBILITY TO HEAVY METAL TOXICITY

The earth's crust naturally contains heavy metals, which are neither destroyed nor deteriorated. Since metal ions are necessary for both organic and inorganic components of life, life cannot exist without them. Numerous metals, including Fe, Co, Cu, Se, and Zn, are necessary. They are found in trace levels in plants, where they aid in metabolism and growth. Yet, there may be negative effects if metal concentrations are higher than what plants require. Soils are exposed to several natural and man-made sources of heavy metal pollution. HMs are taken up by plants from the soil through their roots and then moved to other parts of the plant, where they can cause several harmful consequences. When plants are exposed to harmful levels of heavy metals, they experience a variety of morphological and metabolic alterations. The most prevalent visible indicators of heavy metal stress are decreased plant growth along with leaf necrosis, a drop-in seed germination rate, turgor loss, and impaired photosynthetic equipment (Emamverdian et al., 2015). Moreover, heavy metals affect the absorption of vital metals and obstruct transpiration, transport, nutrition metabolism, and water uptake. Damage to DNA and pro-mutagenic damage, including cross-linking, depurination, and base modification is brought on by metal ions' contact with the cell nucleus and affects biomolecules involved in cell division and cycle (Hossain et al., 2012). According to Singh et al. (2016), there are several processes that HMs use to

interfere with a plant's biological system. These include the removal of essential cations from their attachment sites, which causes functional collapse, rivalry for adsorption that the level of the roots due to resemblance (e.g., As and Cd, P and Zn), interaction with the sulfhydryl group (-SH) of proteins, disruption and deactivation of protein integrity, and harm to macro molecules from reactive oxygen compounds (ROS). Plant HM homeostasis is significantly influenced by transport proteins, including ATPase's (CPx-type), zinc iron-regulated transporter-like protein, diffusion of cation facilitators, and the natural resistance-associated monocyte protein family (NRAMP). The mechanisms and functional roles of these proteins have been thoroughly studied (Ghori et al., 2019). In addition to modifications in physiology, anatomy, and biochemistry, a large group of genes regulate the plant's molecular resistance to harmful heavy metals. This contains regulatory genes that do not code for stress response proteins and those that do. These genes are engaged in a range of biological processes, varying from hormone metabolism and signal transmission to the manufacture of Osmo-protectant solutes and antioxidant chemicals (Singh et al., 2016).

Uptake and transportation of Heavy Metals

When toxic metals are absorbed by root cells, they are transferred to other plant tissues via membrane transporters in search of necessary or advantageous nutrients. This happens as a result of transporter protein promiscuity as well as similarities in the physicochemical characteristics of nutrients and hazardous metals, particularly those elements that belong to the same periodic table group. On the one hand, proteins' capacity to distinguish between extremely similar substances may be limited by physical similarities. Proteins find it difficult to discriminate between arsenate and phosphate because they have almost equal pKa values as well as comparable ionic radius and charge properties (Zhao FJ et al., 2022). Together with a smaller quantity of organic arsenic, the two most common forms of arsenic found in the environment are arsenate [As(V)] and arsenite [As (III)]. One significant element influencing the kind of arsenic present is the redox state of the soil. The high-affinity phosphate transport mechanism allows As(V), a phosphate analog, to enter the root cells (Shukla et al., 2015). However, it has been demonstrated that aquaporins belonging to the nodulin 26-like intrinsic protein (NIP) subfamily transport As(III) into plant cells (Dubey et al., 2018). Phosphate is often more favored by plant phosphate transporters than arsenate. PvPht1;3 from the As hyperaccumulating fern Pteris vittata is interesting in that it has comparable affinities for phosphate and arsenate, with a much greater affinity for arsenate than Arabidopsis PHT1;5 and PHT1;7(DiTusa et al., 2016). When searching for phosphate, organisms inevitably take up arsenate; nevertheless, microbes and plants are able to eliminate the cellular arsenate due to a significant difference in the redox chemistry of the two anions. just like arsenite, but without losing phosphate.

Effect of Lead (Pb)

Lead has extremely harmful impacts on the environment. Even small amounts of Pb can negatively impact a plant's physiological processes inside its cells. It causes the membrane's permeability to change, lowers the water potential, and either boosts or decreases the activity of plant enzymes. The majority of plants absorb lead through their roots, leaves, stems, and seeds. Pb mostly blocks the advent of cations such as Fe+3, K, Ca, Mg, and Cu and anions such as nitrates. Pb has harmful effects on some organelles, including the nucleus, chloroplasts, and mitochondria. Pb lowers the mass of the shoots and roots as well as their length, percentage of germination, germination index, and germination index (Bharti R et al., 2022). Reactive oxygen species including hydrogen peroxide, superoxide anion, and hydroxyl radical were formed as a result of lead poisoning.

Due to their primary targets being lipids, and proteins, especially nucleic acids, reactive oxygen species (ROS) generation might pose a major concern. Because lead creates ROS, it causes oxidative stress. The plant releases more peroxidase ascorbate (APX), catalase, and superoxide dismutase (SOD) antioxidant enzymes in order to defend itself. Lead affects photosynthesis because it suppresses the mechanism of electron transport, reduces the efficiency of Calvin cycle enzymes, and

decreases proton transfer during respiration. Pb lowers the sugar and amino acid concentrations, which affects the tumor pressure. Pb lowers the plant cell wall's plasticity and turgor pressure. Pb inhibits leaf development, resulting in a reduction in leaf surface area and the subsequent Decreased sweating (Ghori et al., 2019). Plants with lead poisoning have reduced growth, chlorosis, necrosis, and inhibition of root development.

Effect of Cadmium (Ca)

One unneeded metal that has an impact on plant growth and development is cadmium. Cadmium's great solubility in fluids and harmful effects even at low levels make it a very significant contaminant. According to Wagner's estimations, the range of Cd concentrations in non-contaminated soil is 0/04 to 0/32 mM, whereas the range for polluted soil is 0/32 to around 1 mm (Zhao et al., 2022). The three most common signs of lead poisoning are leaf rolls, chlorosis, and stunting. Cadmium decreases antioxidants that are both enzyme- and non-enzyme-based and increases the formation of oxygen-free radicals. Because heavy metals are more abrasive, phytotoxic symptoms such as in plant roots, leaf chlorosis, brownish staining, leaf red, and root browning are more frequent. When plants mature, Cd causes all organs to increase their dry fresh mass proportions (DM/FM). High lead concentrations build up in plants and result in some issues that impede their growth and development, including stomata closure, decreased enzymatic activity, nutrient absorption suppression, and issues with respiration and photosynthesis. Reactive oxygen with larger concentrations of ROS is particularly harmful, even though during regular respiration and photosynthesis, species are created in plant cells. It oxidizes several proteins, including fats, catalase, and ascorbate peroxidase, at high quantities, altering cell structure and causing mutagenesis. Cadmium does not seem to have a direct impact on ROS production, in contrast to other heavy metals. Senescence of the leaves, a reduction in carotenoid content, and occasionally even mortality was caused by cadmium. Heavy metals decrease the activity of the enzymes involved in photosynthesis and obstruct the cycle of electron transport. Plants thus generate less chlorophyll.

Effect of Arsenic (As)

One metal that plants do not need is arsenic. Because of its widespread dissemination, arsenic poses a serious environmental danger and is very hazardous to all living things, including plants. Arsenic penetrates plants along with vital elements and affects growth, crop yields, and germination in several ways. The intake of mineral nutrients and the introduction of metalloids and metals depend on water flow. Nonetheless, it has been documented that certain heavy metals have an impact on the water fluxes in several plants (Rathoure et al., 2022). (Bharti R et al., 2022). ROS are the source of oxidative stress, which harms macromolecules such as carbohydrates, proteins, lipids, and DNA. By raising the concentrations of antioxidant enzymes such as catalase (CAT) and superoxide dismutase (SOD), and ascorbate peroxidase, as well as protective non-enzyme like proline, which builds up in plants. Plants defend themselves against oxidative harm by maintaining their water levels, protecting their cell walls, and other mechanisms (Beniwal et al., 2023). Arsenic inhibits the growth of leaves, the plant's fresh, dry bulk, curling, reduced photosynthesis, and leaf blade necrosis. Protein metabolism and energy transfer depend on phosphate, however, because phosphate is absorbed through the phosphate transport system, arsenic has an impact on phosphate intake. Phosphate metabolism is disrupted due to the molecular similarities between As+5 and P+5 (Nagarajan et al., 2024). It also affects other metal concentrations, such as Zn, K, Ca, and Mn. Arsenic damages plants in some ways, including by converting arsenate to arsenite inside plant cells and interfering with aerobic phosphorylation (Tripathi et al., 2018). In addition to causing slowed growth and inhibiting root expansion, arsenic also reduces fruit yield and leaf senescence and can occasionally cause plant mortality.

Effect of Nickel (Ni)

Although nickel is not a major element required for plant growth, it is classified as a heavy metal

because of its toxicity at greater doses. Plant development and growth were impacted by Ni's effects on the environment. A plant is poisonous if its Ni content is more than 100 mg/dm3. Since roots absorb nickel more readily than shoots do, Plant roots are used to evaluate various chemicals for toxicity, including heavy metals. Ni causes plants to undergo chlorosis and necrosis by interfering with the absorption and metabolism of Fe (Bhalerao et al., 2015). Ni stress causes the total moisture deposit and biomass in the less stressed and corresponding portions of plants to decrease, whereas Ni toxicity reduces crop yield, it also damages the structure of the chloroplast and prevents the synthesis of chlorophyll and germination. It has been shown that the shoot/root length ratio decreases as the metal content in the roots/shoot ratio of the seedling increases. While Ni reduces lateral root branching, heavy metals including Zinc, Ag, Cd, and Pb restrict root development at nonlethal amounts without affecting root branching. The intake of mineral nutrients can rise, decrease, or remain constant when Ni is present. The similar ionic ratio of Ni along with other cations at their common binding sites determines the decreasing intake of macro- and micronutrients. Because of their chemical affinity for those elements, organic macromolecules bound by high concentrations of Ni become denatured, disrupt the metabolism of Fe, Zn, and Mg, and are readily replaced (Gautam et al., 2017). The flexibility of the cell wall is reduced by heavy metals because they directly link with pectins and encourage peroxidized activity in the intercellular space and cell wall. As a result of ROS buildup, protein builds up in plants and serves as a marker for different types of stress. Both oxidative stress and disruption of chlorophyll metabolism are brought on by nickel. Elevated Ni concentrations cause disruptions to mitotic root tips and lead to atypical plant flower forms.

Effect of Mercury (Hg)

Mercury is considered a unique metal since it may be found in nature in several forms, such as HgS, Hg+2, and Methyl-Hg. In agricultural soil, hg+2 is the most common of them. Mercury in its ionic form (Hg+2) primarily passes through soil and can accumulate in aquatic organisms (Gomes et al., 2009). Physiological problems and disruptions to plant metabolism are caused by Hg+2. It causes changes in the formation of anthocyanins and chlorophyll and boosts the synthesis of metabolites such as ascorbic acid, which harms plants. Mercury's toxicity is dependent on its chemical form; methyl mercury is more hazardous in its organic form than in its ionic form (Hg+2) (Asati et al., 2016). When Hg combines with SH groups, it forms an S-Hg-S bridge that impacts seed germination and embryo development. The toxic effects of mercury disrupt the morphological system, lower biomass, and slow the development rate of shoots. Chlorophyll is reduced by mercury stress because it impairs photosynthetic processes and reduces the intake of photosynthetic elements (Mn and Fe) (Anuradha et al., 2024). Hg accumulates mostly in roots and to a lesser extent in shoots because Hg ions easily interact with anionic materials to form precipitates that are insoluble and limit simple Hg+2-mobility. Plants have a large number of reactive sites for DNA binding, which means that DNA might bond with Hg and damage plant chromosomes. Additionally, mercury decreases photosynthesis, water intake, and transpiration rate.

IV. PHYSIOLOGICAL RESPONSES OF PLANTS ON METAL TOXICITY

Many physiological reactions in plants are triggered and altered by heavy metal poisoning. These include decreased leaf area index, photosynthetic rate, leaf germination, plant development, and growth, as well as increased leaf chlorosis and cell wall damage. significant HMs, including As, Hg, Co, Cr, Cu, Cd, and many more, have caused significant morphological changes in plants as well as a decline in plant growth and seed germination. Moreover, Pb reduced Brassica juncea L.'s development and growth (Bassegio et al., 2020). Similarly, The roots and shoots of Triticum aestivum died simultaneously from fresh and dried leaves when the concentration of Cd rose from 50 to 200 µM. (Rehman et al., 2021). Additionally, as the Mn level increased from 2 to 1000 µM, a growing trend in the negative effects of Mn toxicity was observed

on the biomass of roots and shoots, the chlorophyll synthesis, photochemical reactions efficiency of PSII, and the stomatal conductivity of Vaccinium corymbosum L. (Millaleo et al., 2020). In Brassica napus, chromium contamination in the soil significantly decreased the height of plants, root length, net the processes of photosynthesis both dry and fresh biomass, and water use efficiency (Zaheer et al., 2022). Furthermore, to avoid interfering with the organelles' metabolic functions, contaminants that have entered root cells are gathered into vessels by the cells. For example, the significance of root HM prevention and relief was demonstrated by Cr deposition and division within the vessels and cell walls of plants of Arabidopsis thaliana (Eleftheriou et al., 2015).

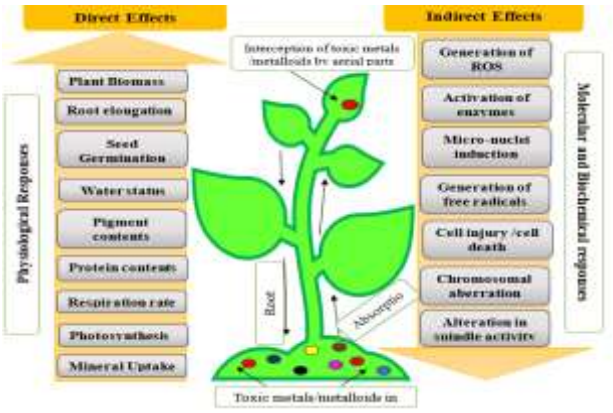

Fig 2: Indirect and direct impacts on agricultural productivity may result from the toxicity of heavy metals and metalloids. Poisonous metals and/or metalloids can interact with plants both above and below ground. Several dangerous metals and metalloids have toxic properties that increase biochemical and molecular reactions while lowering physiological reactions. (Source: Figure generated by author).

It has been shown that the cell plasma membrane controls, shields, and neutralizes undesirable substances from entering the cell organelles and mitigates the negative consequences of various toxicities. Nevertheless, it has been shown that heavy metals like cadmium can damage the structure and function of the plasma membrane, which can result in cell death. The disruption of nutrients and water supplies is only one of the many undesirable changes that can exacerbate these detrimental impacts.

V. BIOCHEMICAL RESPONSES OF PLANTS ON METAL TOXICITY

Heavy metals can enter plant cells by some transporters, including as cation diffusion facilitator (CDF), zin-iron permease proteins (ZIP), heavy metal-transporting ATPases, multidrug and toxin efflux (MATE), and natural resistance-associated macrophages proteins (Nramp). Once inside, they block several functional groups or replace or dispense with essential ions to initiate a series of biological events. For instance, when Vigna radiata was grown in 50% Cr soil, Ruth and colleagues (2019) examined the biochemical reaction and found that the amount of starch, amino acids, nitrogen, and chlorophyll had significantly decreased. Some decorative plants subjected to Cadmium toxicity showed a significant reduction in both overall respiration and the length of their roots as a result of biochemical stress stimuli. Conversely, leaf proline focus, osmotic adjustment, damage to the membrane, soluble sugar level, stability of membranes index, and metal-proline complexes all increased concurrently. In one study, seedlings of Sesuvium portulacastrum subjected to greater concentrations of Cu were unable to produce excessive quantities of ROS and MDA due to activated antioxidants (Lokhande et al., 2020; Sathvara et al., 2024). The proper amounts of ROS are often maintained, balanced, and restored by these antioxidants. The Helaoui group (2020) evaluated the Ni-mediated biochemical reaction, and the findings showed that higher peroxidase (POD) and glutathione S-transferase (GST) concentrations were necessary to counteract ROS-mediated damage. Moreover, heavy metal toxicities have a major impact on carbon fixation, distribution, and absorption. For instance, Triticum aestivum's inability to assimilate CO2 was hampered by toxicities from Cd and Zn. Under the greater concentration of HMs, nitrogen fixation, metabolism, and carbon fixation are all negatively impacted. For instance, in Cyamopsis tetragonoloba exposed to Cr toxicity, The overexpression of protease enzymes led to a reduction in the

production of the enzymes responsible for fixing NH4 and NO3, resulting in enhanced structural breakdown (urease and nitrogenase) (Mishra et al., 2016b).

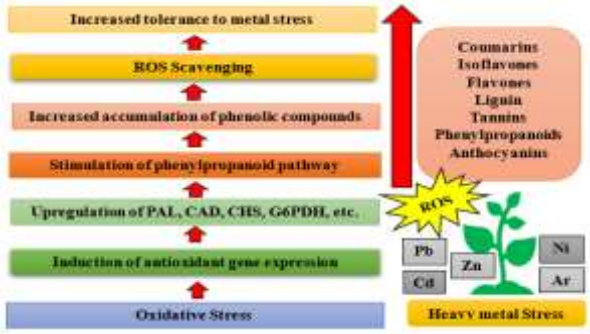

Fig 3. Plant secondary metabolite production: the role of antioxidant mechanisms, heavy metal-induced oxidative stress, and ROS scavenging. (Source: Figure generated by author)

Table 2: A summary of heavy metals' biochemical and physiological effects on plants that have been documented (K. Bashir et al., 2016).

Heavy metal	Plant Species	Stage of Growth	Concentration and longevity of heavy metals	Design Experiments	Effect on Plants	Reference
Pb	Oryza sativa L Brassica juncea	The stages of tillering, heading, and ripening stage of	Soil containing lead particles 136, 362, 1150, and 80 mg kg-1	field study	-inhibited the overall develop-ment of the plant and prevented root elongation Supp-ression of photo-synthetic processes by altering chloro-phyll concentra-tions and producing too much ROS	(Hussain et al., 2020)
Cr	Vigna radiata L.Oryza sativa L.	Plant growth stage and germination	-	Pot experiment	-Decreased stomatal conductance, net photosynthesis, plant height, root ength, fresh and dry biomass, and water use efficiency- delayed and extended the cell cycle, which prevented mitotic cell division.- prevented the breakdown of chlorophyll, amino acids, and carbohydrates by inhibiting the enzymes nitrogenase and urease, which fix NO3 and NH4 +.	(Rath et al., 2019)
Hg	Elodea nuttallii	Vegetative stage	- Hg^{2+} (20 µg L-1) during 7 days	Hydroponic setting	-a disturbed water content and nutritional balance -Lipid peroxidation and excess ROS generation	(Beauvais-Flu¨ck¨ck et al., 2018)
Al	Pinus massoniana	Seedling phase	For forty days, al solutions (10-5, 10-4, 10-3, and 10-2 M) were used. 4.4 mmol L-1 Al3+ throughout the day. 25 hours of Al (25 µmol L-1 AlCl3)	Hydroponic research	-enzymatic regulation is compromised. ROS and antioxi-dants are upregulated -Diminished physiological characteristics, such as levels of chlorophyll and fresh and dry biomass an imbalance in nutrition. -physiological traits, such as dry and fresh biomass, are reduced. disruption of the cytoskeleton's structure and function.	(Zhang et al., 2014)

As	
Hordeum vulgare L.Brassica napus stage For a week, Oryza	
Seedling stage	
Na2HAsO4 at 50 µmol L-1 for two days	
(0, 200 µmol L-1; NaAsO2) over 7 days.	
Controlled growth chambers	
-A surplus of reactive oxygen species and heightened antioxidant enzyme activity - Programmed cell death, thiol transferase activity downregulation, and epigenetic mediation.	
(Shukla et al., 2015)	

VI. MOLECULAR RESPONSE OF PLANTS ON METAL TOXICITY

In reaction to severe food toxicity, plants delayed or momentarily delayed the growth of their roots by interfering with mitotic activity. Plantago lanceolate under Ni stress was shown to have decreased meristem mitosis, which resulted in limited root development and elongation (Ramakrishnan and Jayaraman 2019). Reactive oxygen species (ROS) were created in excess via a metal-mediated molecular mechanism in Heaym species exposed to heavy metal toxicity, according to Hasanuzzaman et al. (2020). Lipid peroxidation, denaturing of protein and nucleic acids, and damage to the membranes of cells were the results of this. Plants provide a variety of cheating representatives, metal-binding agents, or cleansing approaches, such as amino acid organic acids, phytochelatins, a substance called, etc., to counteract the harmful effects of heavy metals (Raza et al., 2022).

Table 3: The absorption and metabolism of HMs in plants. (Angon et al., 2023)

Heavy metals	Plant uptake forms that are available	Plant metabolism	Accumulation	Effect on plants	Reference
Pb	Lead-hydroxy and Pb^{2+} complexes	A non-essential component	Roots	Development of plants, generation of chlorophyll, and germination of seeds	(Ghani *et al.,* 2021) (Yahaghi*et al.,*2019)
Cu	Cu^{2+}	An electron transport is involved in transpiration in plants. A mediator for redox reactions in the mitochondria, chloroplasts, and cytoplasm of cells.	greater in roots than in branches and leaves	Root lengthening, lipid peroxidation expansion, seedling growth, photosynthesis, cell lengthening, and structural changes in the thylakoid membrane.	(Mir Soleimani *et al.,*2023) (Nazir *et al.,* 2019)

Cd	As	Cr
Cd^{2+}	As^{5+}	Cr^{3+} Cr^{6+}
-Non-essential element	- A non-essential component	- A non-essential component
An excessive number of leaves.	Not available in parts that can be eaten, such as roots, shoots, leaves, etc.	Roots
The generation of reactive oxygen species, photosynthesis, intake of nutrients and water, uncontrolled cell division, and necrotic cell death	The breakdown of phosphate	elongation of shoots and roots, cellular division, early plant growth phases when stems and leaves emerge, and metabolic problems affecting seed germination.
(Huybrechts *et al.,* 2021) (Zhu *et al.,* 2021)	(Ali *et al.,* 2022) (Shri *et al.,* 2019)	(Gladkov *et al.,* 2023)

Ni	Zn
Ni^{2+}	Zn^{2+}
Iron uptake/germination of seeds -A crucial element in inducing urease, An enzyme that breaks down nitrogen.	A constituent of the unique zinc finger proteins, which can attach to both RNA and DNA. Enzymes and ribosome-related components, such as oxidoreductases, hydrolases, and transferases.
Fruits, buds, and seeds.	Vacuoles from dividing cells, roots, seeds during senescence, and tonsoplasts.
Blocking the enzymes amylase and protease action, leaf area, the height of the plant, stopping the formation of new lateral roots while damaging the photosynthesis process and hindering root cell division in mitosis are some methods used to limit seed germination and delay plant development.	Photosynthesis, DNA regulation and stability, necrotic spots, hereditary diseases, and plant growth
(Koza *et al.,* 2022) (Khan *et al.,* 2021)	(Natasha *et al.,* 2022) (Kaur *et al.,* 2021)

Plant HMs are highly adaptive and resistant concerning the molecular response when microRNAs are engaged in the control of auxin communication, chelate or antioxidant reaction, and cytokinin signaling. (Ding & associates, 2020). For instance, (Casarrubia et al., 2020) found that microRNAs significantly influence the Vaccinium myrtillus crop's susceptibility to exposure to Cd, working in tandem with the mycorrhizal link. Increased microRNA transcription has been discovered to considerably boost Nicotiana tabacum's ability to tolerate Al and Cd, as seen by the synthesis and biogenesis of several alternative metabolites. Most remarkably, it was shown that Cd exposure causes Carthamus tinctorius to produce transcripts of various microRNAs, namely microRNAs 156, 162, 164, 166, 172, 398, and 408. These transcripts regulate Cd toxicity by controlling the activity of the relevant, targeted genes.

VII. THE EFFECTS OF HEAVY METAL EXPOSURE ON THE ENVIRONMENT

Effect of Metal Toxicity on Soil

The modern world presents a significant risk from heavy metal contamination of the soil. Among other things, the physical attributes of soil are its resistivity, temperature, composition, color, bulk density, permeability, and homogeneity. It is believed that HMs are a major cause of polluted soil. Many different metals, like Cu, Zn, Cd, Pb, Ni, and Cr can lead to heavy metal contamination under soil conditions. The microbial population that produces enzymes is altered by metals, which indirectly impacts the enzymatic activity of the soil.

Physical Properties of soil

High atomic weight and density elements, or HMs, can negatively impact the physical characteristics of soil. These metals consist of Cd, As, Pb, Cr, and Hg. Excessive concentrations of these substances can have detrimental effects on the structure, texture, porosity, and water-holding capacity of soil. HMs have the following effects on the physical qualities of soil

Soil Texture Alteration: The soil's texture may change due to shifts in the distribution of particle sizes and the accumulation of heavy metals within the soil's matrix. Studies have indicated that the proportions of clay, sand, and silt particles in soil are influenced by heavy metals such as nickel and zinc (Wang et al., 2022).

Soil Structure Disruption: By inhibiting the formation and stability of soil aggregates, HMs can change the structure of the soil. Aggregates are essential for preserving the porosity, water penetration capacity, and healthy soil structure. Soil can contract due to aggregate instability brought on by HMs such as Cu, Cd, and Pb (Anuradha et al., 201).

Water-Holding Capacity: Heavy metals (HMs) may affect soil's ability to retain water. Elevated levels of heavy metals (HMs) have the potential to diminish soil porosity and pore connectivity, resulting in a reduced ability to retain water and a rise in water runoff. It's been shown that the accretion of heavy metals like Zn and Cu lowers the soil's water-retention capacity, which increases soil erosion and decreases the quantity of water accessible to plants (Imfeld et al., 2022).

Reduction of Soil Porosity: Contamination with heavy metals can cause a decrease in soil porosity, which can impact nutrient, water, and air movement.

Heavy metals, such as Pb, Cr, and Cd, can block earth pores. This decreases the amount of water that seeps through and prevents roots from growing. (Nisar et al., 2024).

Chemical Properties of Soil

The chemical characteristics of soil can be significantly impacted by heavy metals in the following ways:

- **Nutritional Imbalance:** Heavy metals (HMs) can upset the soil's vital nutritional balance. Certain metals, such as calcium, iron, manganese, and magnesium, can compete with these nutrients and prevent plants from absorbing them. Plants may have nutritional deficits as a result of this interference, which may hinder their development and yield. Lead

is one of the potentially dangerous metals that has an impact on soil fertility, nutrient availability, and microbial diversity (Dotaniya et al., 2020).

- **pH Alteration:** The pH level of soil can be changed by heavy metals (HMs). Metals like cadmium and aluminum, for example, can raise the acidity and lower the pH of soil. Conversely, by increasing the pH of the soil, metals like chromium and nickel can make the soil more alkaline. These variations can affect microbial activity, nutrient availability, and the overall health of the soil. The pH and the microbial content of the soil are the two main determinants of the concentration and distribution of heavy metals. Hu, W.Y., et al. (2018).
- **Redox Reactions:** HMs have the power to affect redox reactions in soil, which can change the nutrients' mobility and availability. For instance, soil's oxidation and reduction states can be changed by redox processes involving metals like iron and manganese. These processes may have an impact on nutrient transformations, including the conversion of sulfur and nitrogen molecules, as well as soil fertility.
- **Adsorption and Extraction:** In the soil, heavy metals (HMs) can go through adsorption and desorption processes that impact their availability and mobility. The organic matter concentration and clay mineral content of the soil are important factors in heavy metal adsorption. Two examples of heavy metals (HMs) that are highly adsorbed to soil particles and have a strong affinity for them are lead and cadmium. This reduces the HMs' bioavailability to plants (Sathvara et al., 2024).

Effect of Metal Toxicity on Soil Micro-organisms

Lead, arsenic, nickel, chromium, cadmium, and mercury are examples of heavy metals distinguished by their comparatively large atomic weight and high density. These naturally occurring substances are released into the air, water, and soil as a result of mining, farming, industrial activities, and the usage of certain goods by humans. They can accumulate in living things due to their poisonous nature, which can cause serious environmental problems. They damage soil microbes, which are essential to the health of ecosystems and soil fertility. The general well-being and productivity of soil ecosystems are impacted by the many noteworthy effects that HMs have on soil microorganisms (Ali et al., 2019). Since HMs harm microbial cells, their presence in the soil largely prevents microbes from growing and developing, which reduces the number of microorganisms in the soil. Lead, the element mercury, and cadmium are among the metals that wreak havoc on microbes. The nitrification and the process of n cycles, which lower the soil's overall availability of nutrients and degrade pollutants, might also be hampered by this drop in microbial biomass (Maurya et al., 2021). These harmful heavy metals not only restrict development but also impede enzymatic activity, which is crucial for performing basic metabolic functions. The conversion of nutrients and the breakdown of organic molecules by flora into useful procedures are examples of these metabolic processes. These cycles and the bioavailability of nutrients can become unbalanced in the presence of excessive HMs. As a result, the soil's fertility is decreased, which lowers production and hinders the plant's ability to grow and develop fully (Jain et al., 2016). A few types of microorganisms are extremely vulnerable to increased HM concentrations. It lowers population diversity and negatively affects the ecosystem's capacity to remain stable and operate. Similarly, a process known as bioaccumulation allows some types of microbes to grow resistant to heavy metal stress. They may therefore build up in the tissue of the microorganisms, raising the concentration in their biomass and impacting both the bacteria and the higher trophic levels of the food chain (Abdu et al., 2017). They may also interfere with the symbiotic connections that plants, microbes, and mycorrhizal fungi have. They may also hinder the uptake of nutrients and restrict the expansion and maturation of plants. The pH of the soil is also significantly maintained by soil bacteria. Microorganisms are disturbed by soil pH levels that are too high or too low. Soil pH fluctuations can be caused by heavy metals (HMs). The soil may become more acidic due to the presence of some

heavy metals, such as aluminum, which would lower the pH. Because various species are more or less resilient to pH variations, the fluctuation in pH may affect the survival and functioning of soil-based microorganisms (Anuradha et al., 2018). Methylmercury, a toxic form of mercury that can bioaccumulate into the dietary chain and threaten higher trophic level organisms, is produced by certain soil bacteria and fungi. This also has an impact on the marine food chain (Naz et al., 2022).

Effect of HMs on Soil Microbiomes and Their Support in Plant Growth Mechanisms

Mycorrhizal fungi and plants form a symbiotic relationship that goes beyond the plants' ability to better absorb nutrients and water. In the face of HM stress, certain mycorrhizal fungi become strong allies, helping to reduce the uptake of heavy metals by the plants and providing extra protection against metal toxicity (Mbodj et al., 2018). The beneficial relationship between specialist fungus and the roots of cereal plants is known as mycorrhizal symbiosis. Arbuscular mycorrhizae (AM) and ectomycorrhizae (ECM) are the two forms of mycorrhizal connections that are most prevalent. The hyphal networks of these mycorrhizal fungi spread into the surrounding soil, so expanding the reach of cereal plant roots and improving their access to water and nutrients (Khan et al., 2022). The availability and absorption of heavy metals by plants can be strongly impacted by mycorrhizal fungus under conditions of heavy metal stress. Certain mycorrhizal fungi have the unusual capacity to absorb or immobilize heavy metals from the soil, therefore serving as a buffer between plants and metal toxicity (Dhalaria et al., 2020). Additionally, through their metabolic processes, mycorrhizal fungi can affect the pH of the soil in the rhizosphere. Mycorrhizal fungi have the ability to modify soil pH through the release of organic acids and other chemicals, which can impact the solubility of heavy metals. The production of metal precipitates can be facilitated by altered soil pH, which reduces the amount of metals that plants can absorb. Certain mycorrhizal fungus cause the host plant to produce genes linked to heavy metal detoxification. The capacity of plants to withstand heavy metal stress and preserve cellular integrity is further strengthened by this improvement of metal detoxification processes in plants (Bano et al., 2013). Mycorrhizal fungi promote plant growth and decrease the absorption of heavy metals by plant roots by a number of ways, such as improved soil structure, competitive exclusion of heavy metals, facilitated nutrient uptake, stimulation of plant defense mechanisms, pH modification, and VIIIincreased tolerance.

Depending on the kind of mycorrhizal fungus, the plant species, and the heavy metal in issue, several processes may be at play. Furthermore, the kind of fungus that mycorrhizal fungi are, the soil's composition, the quantity and bioavailability of heavy metals, and other variables all affect how well they reduce the absorption of heavy metals by the soil (Henao and Herrera et al., 2021). Because their efficacy varies depending on a number of circumstances, including the kind of heavy metal present in the soil and the fungal species, not all mycorrhizal fungi offer the same amount of protection against heavy metal absorption.

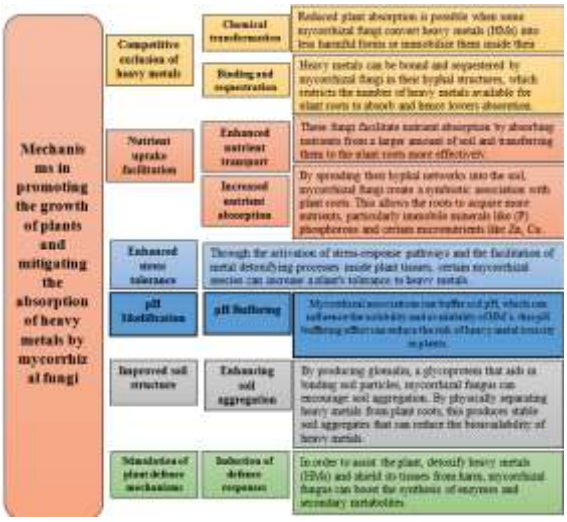

Fig 4: An illustration of the processes by which mycorrhizal fungi improve plant health and lower the absorption of HMs in roots through Défense stimulation, heavy metal sequestration, and nutrient facilitation. (Source: Figure generated by author)

Nonetheless, the resistance of cereal crops in settings polluted with metals is facilitated by their general function in augmenting nutrient absorption, strengthening soil structure, and

promoting plant health (Li et al., 2022). The variety of mycorrhizal fungi and their potential to improve plants' resistance to heavy metals are being intensively investigated by researchers.

VIII. THE IMPACT OF HEAVY METAL BIOACCUMULATION IN THE FOOD CHAIN ON HUMAN HEALTH

Due to the harmful consequences that heavy metal pollution has on human health, it is one of the most urgent issues about food security and safety (Motesharrei et al., 2020). The distribution and bioaccumulation of HMs in terrestrial environments vary greatly. Related research has been published recently, mostly concentrating on the transmission of HMs in the terrestrial invertebrate food chain. However, the species and food chains that were studied were comparatively solitary. Heavy metals can enter the body in a number of ways, such as via eating food crops grown in contaminated soil, breathing in dust, absorbing soil through the skin, and so on. (Sanjeevi et al., 2011). The World Health Organization reports that some Zn, Ar, Pb, Cu, Cr, and Cd concentrations exceed the maximum tolerable limits (MTLs). Increased toxicology and the entry of pollutants (heavy metals) into food chains are caused by a variety of circumstances. These include handling small metal compounds in poultry and fish feed poorly, utilizing HM-rich irrigation water, applying HM-containing insecticides and fertilizers, and managing industrial effluent inappropriately. This is known as heavy metal contamination (Zakir et al., 2020). For humans, even small concentrations of HMs pose a serious risk. Oral consumption of lead, mercury, arsenic, or cadmium can cause poisoning in humans or animals that is either acute or long-lasting. Heavy metal poisoning causes a variety of symptoms, including nausea, vomiting, diarrhea, irregularities in the motor neurons, visual and hearing issues, damage to the heart and brain, and hypertension (Mari et al., 2018). Their exposure has deleterious effects on major organs such as the kidney, brain, reproductive system, digestive system, and central nervous system. Additionally affected include the neurologic system, brain, kidneys, and circulatory system in children (Kumar et al., 2019). Additionally, nerve cell operation, mitochondria metabolic functions including oxidative phosphorylation, ATP synthesis & DNA structure can all be damaged by internal and cellular toxicity. Regularly consuming food contaminated with dangerous heavy metals may have disastrous effects, possibly leading to the apocalyptic end of humankind

Table 4: Toxic mechanisms and effects of Heavy metals on human health.

Heavy Metal	Toxicity in organs	Disrupted macromolecule or action mechanism	References
Arsenic (Ar)	- Liver Damage - GI Discomfort - CNS Injury - Skin & Hair colour changes - Cardiovascular dysfunction	-Modifications to the equilibrium of neurotransmitters -Uncoupler of oxidative phosphorylation, which prevents the synthesis of ATP. -Thiol conjugation (GSH binding) -Capillary endothelium injury	(Shekhawat *et al.*, 2015)
Cadmium (Cd)	-Cancer -Disorder in metabolism of Cu and Zn. -Lung injuries -Kidney disfunction - Degenerative bone diseases - Liver damage - GI disorders	- generation of ROS, Modified chains of phosphorylation - low PTH levels in serum - homeostasis, Ca, Zn, and Fe dysregulation - Apoptosis - deregulation of miRNA expression -Endocrine system stress - Kidney absorption of Cd-MT	(Fay.*et al.*, 2018).

Chromium (Cr)	- malignancies of the lungs, throat, bladder, kidneys, testicles, bone, and thyroid are becoming more common -Dermal disease -GI disorders -Kidney disfunction	- Generation of ROS and oxidative stress - Instability in the genome - Damage to DNA	(Deng *et al.*, 2019)
Lead	- Cardiovascular dysfunction - Reduced pulmonary function - Liver damage - GI colic - Hematological changes (Anemia) - Lung's dysfunction - CNS injury	- Lower levels of CAT, GPx, SOD, and GSH - Heme biosynthesis suppression via ferrochelatase and δ-ALAD inactivation -Serum ET-1, NO, and EPO levels elevated -TNF-α, IL-6, and -1β in the CNS - An increase in IL, an inflammatory cytokine	(Boskabady *et al.*, 2016
Mercury	- Hepatotoxicity - GI ulceration - Renal dysfunction - CNS injuries	- Thiol conjugation (GSH binding) - Inhibition of enzymes - Production of ROS - Hydroporins mRNA decrease -Inhibition of glutathione peroxidase - Enhanced expression of C-Fos	(Zhang et. al., 2020)

Remediation of Heavy Metal Toxicity

To safeguard ecosystems and human health, HM pollution in water, soils, and other environmental media must be remedied. Several approaches may be used, each with pros and cons of its own. Remediation of heavy metal pollution makes use of many techniques. Numerous techniques, such as chemical, biological, and physical ones, are feasible. One can employ the exchange of ions and the absorption approach. Metals are bound by adsorption processes using materials like activated carbon or biochar, then filtered out of water by membrane technologies like reverse osmosis. Ion exchange swaps out toxic metal ions for innocuous ones, and sophisticated oxidation techniques alter metal speciation to facilitate removal. The budget, legal restrictions, and contaminated scenario all influence the procedure that is used. While soil washing uses solutions to remove metals from contaminated soil, physical procedures such as excavation transfer contaminated dirt to designated landfills (Vardhan et al., 2019). Chemical methods include employing binders to harden metals or electric currents to transport them toward collecting locations. Biological techniques make use of microorganisms or plants that may absorb or leach metals (Chakrabartty et al., 2021).

Fig 5: Classifications of heavy metal pollution remediation. (Source: Figure generated by author)

Future Perspectives and Research Gaps

Certain research gaps were discovered during our investigation. To encourage more research on HMs, we have included a few possible recommendations. Heavy metal (HM) integration into crops is a crucial component of sustainable agriculture. By shedding light on the process of developing crop varieties resistant to metals, it can assist in reducing the negative effects of polluted soil on agricultural production and health. Understanding how heavy metals (HMs) survive and migrate over plant generations may help in the development of remediation techniques for contaminated settings, such as phytoremediation systems that use plants to extract toxins from the soil. Scientific research on agricultural genetic diversity and plant adaption mechanisms is quite limited. The susceptibility and tolerance of different plant species to heavy metals varies depending on their genotype. Knowledge of how different genotypes and plant species respond to environmental stressors, which might prevent the development of agricultural variations that are resistant to metals. Closing this gap is critical since it has the potential to influence agricultural practices in contaminated regions, offer valuable insights into plant resilience, and support environmental remediation initiatives. This

multidisciplinary field of study has significant ramifications for both environmental preservation and sustainable agriculture. Inter professional collaboration between the domains of toxicology, soil science, and plant biology is required for these study topics. Scientists can aid in the creation of long-term solutions to reduce heavy metal pollution, protect ecosystems, and ensure food security.

IX. CONCLUSION & RECOMMENDATIONS

Most heavy metals are dangerous and harm the ecosystem. Heavy metals may easily enter plants and people due to their lack of biodegradability and water solubility, which might have detrimental effects. Their primary sources of emission are natural and anthropogenic processes within the environment. Plants that are exposed to heavy metals experience growth inhibition, reduced physiological and biological activity, and various forms of resistance to heavy metal detoxification. It lists significant heavy metals that are present in the environment, such as Pb, Ni, Cd, and Cr, and emphasizes how their harmful effects have an adverse influence on agricultural productivity. Ingesting tainted plant items can lead to severe illnesses that impact several organs and jeopardize human health. We hope that this work will significantly advance the field of heavy metals research to address the global issues related to soil, plant, and human wellness caused by HM toxicity.

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